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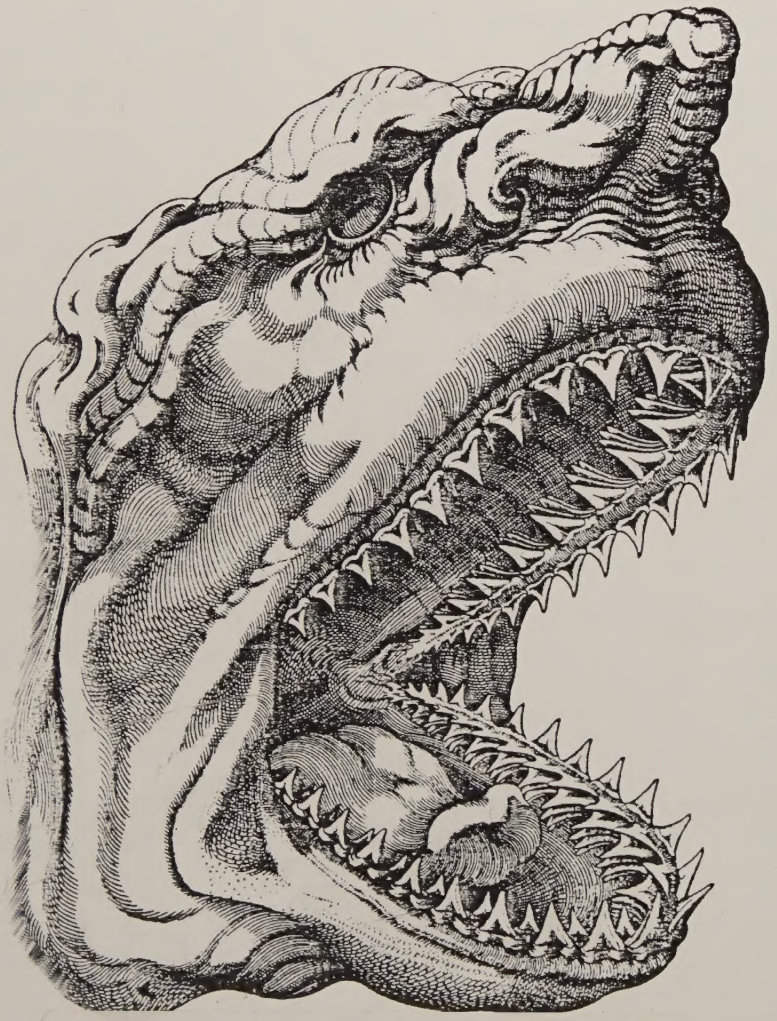

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A HISTORY OF SHARKS

Marine Fisheries REVIEW

W. L. Hobart, Editor
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On the cover:
Nicolaus Steno's 1668 drawing of the head of a White Shark (Maar, 1910).

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Historical Knowledge of Sharks: Ancient Science, Earliest American Encounters, and American Science, Fisheries, and Utilization

JOSÉ I. CASTRO

Ancient Science and History

In western civilization, the knowledge of the elasmobranch or selachian fishes (sharks and rays) begins with Aristotle (384–322 B.C.). Two of his extant works, the "Historia Animalium" (Aristotle, 1970) and the "Generation of Animals" (Aristotle, 1979), both written about 330 B.C., demonstrate knowledge of elasmobranch fishes acquired by observation. Roman writers of works on natural history, such as Aelian and Pliny, who followed Aristotle, were compilers of available information. Their contribution was that they prevented the Greek knowledge from being lost, but they added few original observations. The fall of Rome, around 476 A.D., brought a period of economic regression and political chaos. These in turn brought intellectual thought to a standstill for nearly one thousand years, the period known as the Dark Ages. It would not be until the middle of the sixteenth century, well into the Renaissance, that knowledge of elasmobranchs would advance again. The works of Belon, Salviani, Rondelet, and Steno mark the beginnings of ichthyology, including the study of sharks and rays.

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The knowledge of sharks and rays increased slowly during and after the Renaissance, and the introduction of the Linnaean System of Nomenclature in 1735 marks the beginning of modern ichthyology. However, the first major work on sharks would not appear until the early nineteenth century. Knowledge acquired about sea animals usually follows their economic importance and exploitation, and this was also true with sharks. The first to learn about sharks in North America were the native fishermen who learned how, when, and where to catch them for food or for their oils. The early naturalists in America studied the land animals and plants; they had little interest in sharks. When faunistic works on fishes started to appear, naturalists just enumerated the species of sharks that they could discern. Throughout the U.S. colonial period, sharks were seldom utilized for food, although their liver oil or skins were often utilized. Throughout the nineteenth century, the Spiny Dogfish, Squalus acanthias, was the only shark species utilized in a large scale on both coasts. It was fished for its liver oil, which was used as a lubricant, and for lighting and tanning, and for its skin which was used as an abrasive. During the early part of the twentieth century, the Ocean Leather Company was started to process sea animals (primarily sharks) into leather, oil, fertilizer, fins, etc. The Ocean Leather Company enjoyed a monopoly on the shark leather industry for several decades. In 1937, the liver of the Soupfin Shark, Galeorhinus galeus, was found to be a rich source of vitamin A, and because the outbreak of World War II in 1938 interrupted the shipping of vitamin A from European sources, an intensive shark fishery soon developed along the U.S. West Coast. By 1939 the American shark leather fishery had transformed into the shark liver oil fishery of the early 1940's, encompassing both coasts. By the late 1940's, these fisheries were depleted because of overfishing and fishing in the nursery areas. Synthetic vitamin A appeared on the market in 1950, causing the fishery to be discontinued. During World War II, shark attacks on the survivors of sunken ships and downed aviators engendered the search for a shark repellent. This led to research aimed at understanding shark behavior and the sensory biology of sharks. From the late 1950's to the 1980's, funding from the Office of Naval Research was responsible for most of what was learned about the sensory biology of sharks.

Aristotle was the first to point out, in the "Historia Animalium," the main anatomical difference between male and female elasmobranchs, male claspers: "In some selachia the male differs from the female in having two appendages hanging down near the residual vent, whereas these are not present in the female. The dogfishes illustrate this: it is a difference found in all such fishes" (Aristotle, 1970:109).

Similarly, Aristotle was the first to understand that in many elasmobranchs, the embryos are first nourished by yolk stored in a yolk sac, and afterwards by a placenta formed between mother and offspring. "Selachia and vipers, though they bring forth their young alive externally, first of all produce eggs internally" (Aristotle, 1979:31). "The smooth dogfish…the young are produced with the umbilical cord attached to the uterus, so that as the substance of the egg gets used up the embryo's condition appears to be similar to what is found in quadrupeds" (Aristotle, 1970:261).

ABSTRACT—In western civilization, the knowledge of the elasmobranch or selachian fishes (sharks and rays) begins with Aristotle (384–322 B.C.). Two of his extant works, the "Historia Animalium" and the "Generation of Animals," both written about 330 B.C., demonstrate knowledge of elasmobranch fishes acquired by observation. Roman writers of works on natural history, such as Aelian and Pliny, who followed Aristotle, were compilers of available information. Their contribution was that they prevented the Greek knowledge from being lost, but they added few original observations. The fall of Rome, around 476 A.D., brought a period of economic regression and political chaos. These in turn brought intellectual thought to a standstill for nearly one thousand years, the period known as the Dark Ages. It would not be until the middle of the sixteenth century, well into the Renaissance, that knowledge of elasmobranchs would advance again. The works of Belon, Salviani, Rondelet, and Steno mark the beginnings of ichthyology, including the study of sharks and rays.

The knowledge of sharks and rays increased slowly during and after the Renaissance, and the introduction of the Linnaean System of Nomenclature in 1735 marks the beginning of modern ichthyology. However, the first major work on sharks would not appear until the early nineteenth century. Knowledge acquired about sea animals usually follows their economic importance and exploitation, and this was also true with sharks. The first to learn about sharks in North America were the native fishermen who learned how, when, and where to catch them for food or for their oils. The early naturalists in America studied the land animals and plants; they had little interest in sharks. When faunistic works on fishes started to appear, naturalists just enumerated the species of sharks that they could discern. Throughout the U.S. colonial period, sharks were seldom utilized for food, although their liver oil or skins were often utilized. Throughout the nineteenth century, the Spiny Dogfish, Squalus acanthias, was the only shark species utilized in a large scale on both coasts. It was fished for its liver oil, which was used as a lubricant, and for lighting and tanning, and for its skin which was used as an abrasive. During the early part of the twentieth century, the Ocean Leather Company was started to process sea animals (primarily sharks) into leather, oil, fertilizer, fins, etc. The Ocean Leather Company enjoyed a monopoly on the shark leather industry for several decades. In 1937, the liver of the Soupfin Shark, Galeorhinus galeus, was found to be a rich source of vitamin A, and because the outbreak of World War II in 1938 interrupted the shipping of vitamin A from European sources, an intensive shark fishery soon developed along the U.S. West Coast. By 1939 the American shark leather fishery had transformed into the shark liver oil fishery of the early 1940's, encompassing both coasts. By the late 1940's, these fisheries were depleted because of overfishing and fishing in the nursery areas. Synthetic vitamin A appeared on the market in 1950, causing the fishery to be discontinued. During World War II, shark attacks on the survivors of sunken ships and downed aviators engendered the search for a shark repellent. This led to research aimed at understanding shark behavior and the sensory biology of sharks. From the late 1950's to the 1980's, funding from the Office of Naval Research was responsible for most of what was learned about the sensory biology of sharks.

Aristotle was also the first person to write about what we now call "nurseries" (Castro, 1993; Simpendorfer and Milward, 1993), areas where the females give birth to their young and where the young find food and safety during their early life: "The selachia come in from the high seas and out of the deep water towards land and produce their young there; this is for the sake of the warmth and because they are concerned for the safety of their young" (Aristotle, 1970:265). Nothing else would be added to the knowledge of elasmobranch nurseries for over two thousand years.

Roman writers of natural history works, such as Aelian and Pliny, who followed Aristotle, were compilers of available information. Their contribution was that they prevented the Greek knowledge from being lost, but they added few original observations. Pliny the Elder (A.D. 23–79) expanded Aristotle's comments on the "holy fish" and first recorded interactions between divers and sharks:

"The number of dog-fish[1] specially swarming round sponges beset the men that dive for them with grave danger...Divers have fierce fights with the dog-fish; these attack their loins and heels and all the white parts of the body. The one safety lies in going for them and frightening them by taking the offensive; for a dog-fish is as much afraid of a man as a man is of it, and so they are on equal terms in deep water. When they come to the surface, then the man is in critical danger, as the policy of taking the offensive is not available while he is trying to get out of the water, and his only safety is in his comrades. These haul on the rope tied to his shoulders; his, as he carries on the duel, he shakes with his left hand to give a signal of danger, while his right hand grasps his dagger and is occupied in fighting. Most of the time they haul gently, but when he gets near the boat, unless with a quick heave they suddenly snatch him out of the water, they have to look on while he is made away with.. And often when divers have already begun to be hauled up they are snatched out of their comrades' hands, unless they have themselves supplemented the aid of those hauling by curling up into a ball. Others of the crew of course thrust out harpoons, but the vast beast is crafty enough to go under the vessel and so carry on the battle in safety. Consequently divers devote their whole attention to keeping a watch against this disaster; the most reliable token of safety is to have seen some flat-fish, which are never found where these noxious creatures are—on account of which divers call them the holy fish." (Pliny, 1997:Book 9, LXX:265).

The fall of Rome, around 476 A.D., brought a period of economic regression and political chaos; these in turn brought intellectual thought to a standstill. The Dark Ages had begun, and for the next thousand years there was little intellectual advancement.

The Dark Ages, from the 6th to the 14th centuries in Europe, are also called the Middle Ages, denoting the time from the Classical Greco-Roman Age to the Renaissance. Today most historians use the term "Middle Ages," in appreciation of whatever advances occurred elsewhere in that time. However, as far as intellectual thought and observational science in Europe, those times were dark indeed, and I believe that the term Dark Ages is justified.

During the Dark Ages, the emphasis was not in creating new works but in preserving and transmitting the available knowledge. Originality and the recording of personal observation, common in Greco-Roman works, were usually absent in medieval works. Thus ancient works were copied, often in monasteries, and facts were recorded based on the authority of previous authors.

With the coming of the Dark Ages, much of the existing knowledge of the Greco Roman Era was lost. One medieval work, "The Etymologies" (Barney et al., 2011), was significant in preserving and transmitting knowledge from classical times to medieval times. This work was an encyclopedia of the ancient Greco-Roman and early Christian knowledge, compiled by Isidore (~560–636 A.D.), Bishop of Seville, in the early part of the seventh century. "The Etymologies" was arguably the most influential book, after the Bible, in the learned world of the Latin West for nearly a thousand years (Barney et al., 2011). The work has been referred to as "the entire Middle Ages as a basic book" (Curtius, 1953).

Isidore covered the available knowledge in grammar, mathematics, medicine, laws and crimes, religion, animals, human anatomy, the cosmos, geology, stones and metals, buildings, rural matters, war, games, ships, and hundreds of other subjects, also giving the origins or etymologies of relevant names and words. By the year 800 A.D., copies of "The Etymologies" were found in all the cultural centers of Europe (Barney et al., 2011).

Although many marine and freshwater fishes are named in "The Etymologies," and their names and habits explained, there is little mention of elasmobranch fishes. There is an indirect reference to dogfish, "People gave names to livestock and beasts and flying animals before naming fish, because the former were seen and recognized before. Later as the types of fish gradually came to be known, names were established based on either similarity to land animals or their particular appearance or behavior.... Based on land behavior, such as 'dogs' in the sea [*canes in mare*], so called from land dogs because they bite."

Although Isidore had obviously read some of Aristotle's works, nothing from the "Historia Animalium" or the "Generation of Animals" made it to "The Etymologies." The only mention of a selachian is that "The electric ray (torpedo) is named because it makes the body become numb (torpescere) if anyone touches it while it is alive" (Barney et al., 2011:262), and this is taken from Pliny. After this, the

[1]The term dog-fish or seahound was used for large and small sharks. According to Aelian "There are three kinds of Sea-hound. The first is of enormous size and may be reckoned among the most daring of sea monsters. The others are of two kinds, they live in the mud and reach about a cubit in length. Those that are speckled one may call *galeus* (small shark), and the rest, if you call them Spiny Dog-fish you will not go wrong." (Aelian, 1971:I, 55:73)

Greek knowledge of sharks and other cartilaginous fishes was lost until the Renaissance.

During the Dark Ages, the available knowledge of animals was contained in works such as the "Physiologus" and the "bestiaries." The "Physiologus" was a collection of simple allegorized tales of animals and plants, and it was one of the most popular and widely read books of the Dark Ages (Curley, 1979). It is probably Egyptian in origin, and it was in circulation by 140 A.D. Latin translations existed by 350–500 A.D. The Physiologus engendered the "bestiaries" of the 12th and 13th centuries. The bestiaries were medieval books of "beasts," depicting real and imaginary creatures, and most bestiaries were created in England between 1150 and 1290 A.D. The bestiaries are often beautifully illustrated, e.g., the splendid "Book of Beasts, a facsimile of Ms. Bodley 764" (Bodleian Library, 2009), and its English translation by Barber (1992). In the bestiaries, the first portion of the description, when the creature really exists, is often accurate and based on observation; the second part is usually an allegory.

Fishes are seldom included in the bestiaries. The few illustrations of fishes in the bestiaries include horse-like or dragon-like creatures, as well as good depictions of penguins (Spheniciidae), which were considered fishes. Elasmobranch fishes are generally absent in the bestiaries, with the mention of dogfishes being the exception (probably from "The Etymologies"?).

Why are elasmobranchs absent from the "Physiologus" and from bestiaries? The main reason for the loss of the knowledge is that medieval man did not come in contact with elasmobranch fishes. Medieval men fished mainly in rivers, and there were no freshwater elasmobranchs in Europe. Medieval rivers were relatively unpolluted and teemed with fish; medieval man did not need to travel to the ocean to obtain fish. A school ditty used by Aelfric, a Wessex schoolmaster in 987–1002 A.D., to instruct students in the various occupations (Lacey and Danziger, 1999) explains much about fishing in the year 1000:

> Master: "Which fish do you catch?"
> Fisherman: "Eels and pike, minnows and burbot, trout and lampreys."
> Master: "Why don't you fish the sea?'
> Fisherman: "Sometimes I do, but rarely, because it is a lot of rowing for me to the sea."

During the Dark Ages, knowledge about animals from the classical authors was preserved by copying in monasteries and later by translation and transcription in the Islamic world. The ancient works being copied were then about a thousand years old. Little was added to the available knowledge during that time, because original thought and observation were not encouraged.

With the beginning of the fourteenth century, the revival of knowledge known as the Renaissance started to flourish. However it would not be until the middle of the sixteenth century, with the beginnings of ichthyology, that knowledge of elasmobranchs would advance again.

The conditions of the times would create three men, all born within 10 years of each other, who would lay the foundations of comparative anatomy and ichthyology. They were Pierre Belon (1517–1564), Ippolito Salviani (1514–1572), and Guillaume Rondelet (1507–1566), and all were trained as medical men. Unlike their predecessors over the previous millennium, these men wrote about animals that they observed and examined by themselves, and faithfully illustrated them.

Pierre Belon was born near Le Mans, France. He studied medicine in Paris, receiving a doctor's degree, but it is uncertain if he ever practiced medicine (Gudger, 1934). He was a naturalist best known for his "L'Histoire de la Nature des Oyseaux," which was said to be the best ornithological work produced in the sixteenth century. In this work he represented two facing figures of the skeletons of a human and a pigeon, labeling the homologous bones. For this work he is often considered the founder of comparative anatomy. Later, in 1551, he published "L'Histoire Naturelle des Estranges Poissons Marins." At the time, all aquatic creatures were considered fishes, so this work is mainly about the dolphin (Delphinidae) and secondarily about the hippopotamus, *Hippopotamus amphibious*; and the nautilus, *Nautilus* spp. Only ten fishes are described in Belon's work, including two sharks, but all the descriptions are clear and are accompanied by accurate woodcut illustrations. They are sufficient to identify the species.

Ippolito Salviani, professor of medicine in Rome and physician to popes Julius III, Marcellus II, and Paul IV, would produce a large treatise on fishes in 1554, the "Aquatilium Animalium Historiae," with excellent illustrations of sharks (Fig. 1 and 2). The beauty and accuracy of the engravings were not surpassed until the nineteenth century.

Guillaume Rondelet, studied medicine at Montpelier, and he was the most remarkable of the trio. He wrote the most comprehensive work, the "L'histoire Entière des Poissons," a 1558 French abridgement of his previous Latin works. Although Rondelet's figures are woodcuts, inferior in beauty and quality to Salviani's engravings, the descriptions are accurate and the illustrations are recognizable images (Fig. 3) of 22 species of rays and 13 of sharks, and they are accompanied by notes on their natural history or habits.

The study of the anatomy of sharks also began in this period, with the works of Nicolaus Steno[2], born in Copenhagen, Denmark, in 1638. He studied medicine and the related branches of the natural sciences at the University of Copenhagen where at the time these studies were being pursued with great zeal by a series of great scholars (Maar, 1910).

Steno was the first person since Aristotle to make observations and descriptions of the anatomy of elasmo-

[2] His original Danish name was Niels Steensen. The Latinized form Nicolaus Steno is normally used these days. Also seen as Nicolai Stenonis.

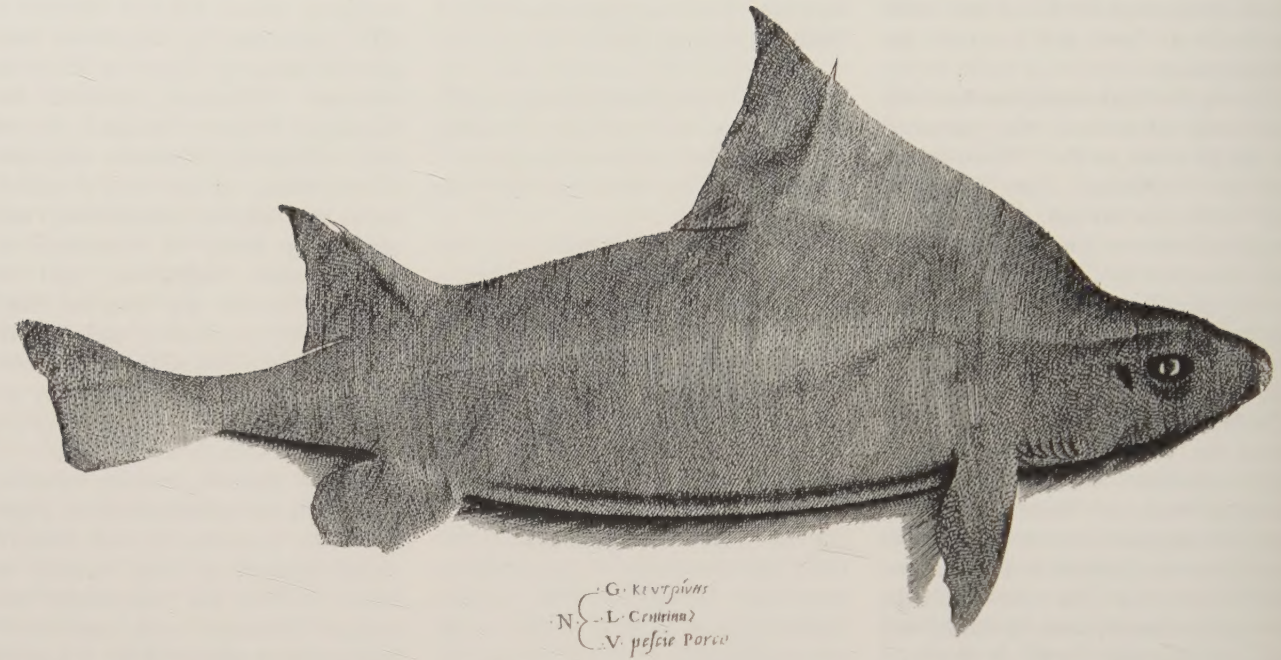

Figure 1.—Salviani's (1554) engraving of the shark *Oxynotus centrina*. The quality and accuracy of his fish engravings would not be surpassed until the nineteenth century. The name is given in Greek, Latin, and vulgate.

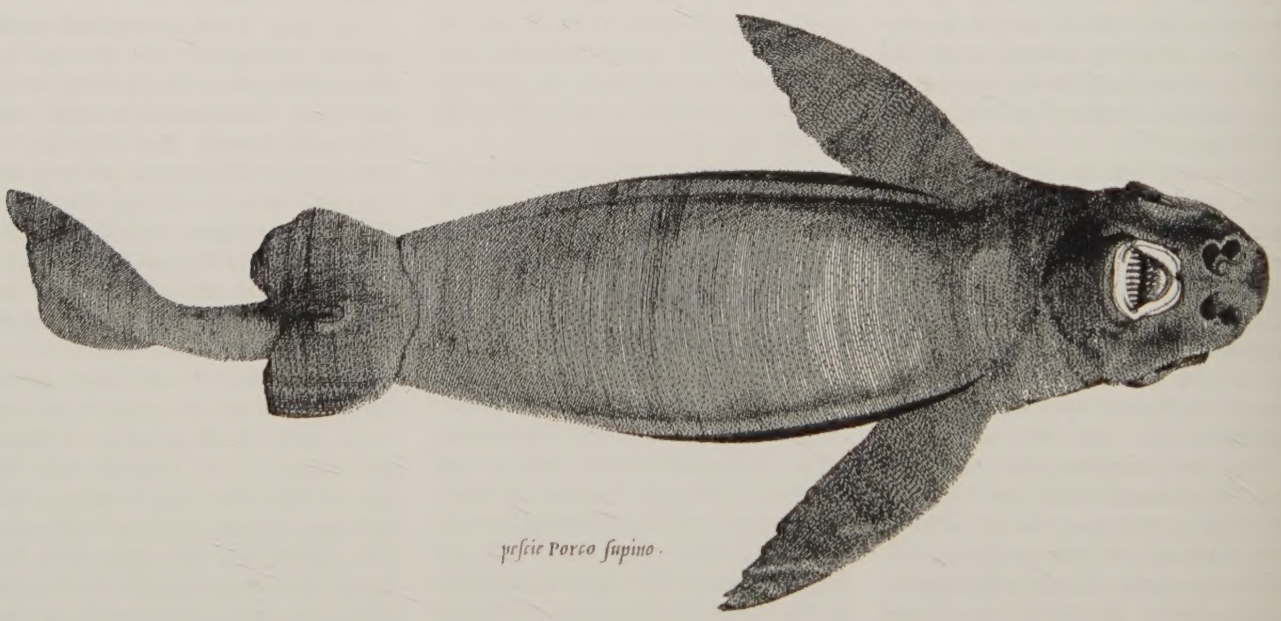

Figure 2.—Salviani's ventral view of *Oxynotus centrina*.

branchs. Steno rediscovered the placenta in the Common Smooth-hound, *Mustelus mustelus*, apparently not being aware of Aristotle's descriptions, and he also went on to describe the anatomy of the digestive systems of two rays. Steno is probably best known for his publication on the dissection of the head of a white shark, "Canis Carchariae Dissectum Caput."[3] This publication is not only an anatomical description of the skin, eye, brain and teeth of the shark (Fig. 4), but in a series of postulates, Steno laid the foundation for scientific geology and paleontology.

[3]For a translation of this seminal publication, see Garboe (1958).

In the early seventeenth century the nature of fossils was unknown, and fossils were assumed to be just particles that resembled plants or animals and there was much confusion about their origin. Fossilized shark teeth were known as "glossopetrae" and were often said to be the tongues of serpents or dragons. Observing the large teeth of the shark, Steno noted the close resemblance to fossilized shark teeth. One of the naturalists of the era, Fabio Colonna, had already stated years earlier that glossopetrae were nothing but sharks teeth in a petrified state. Steno shared that opinion, realizing that what was true for shark teeth was true for other fossils: they had all once been living organisms that had been encased in soils that had eventually petrified, and that former marine sediments had hardened and were now on land. Steno summed up the origins of fossils in his sixth postulate: "Nothing seems to oppose the opinion that the bodies dug out of the ground and looking like parts of animals should be considered as parts of animals" (Garboe, 1958:35). Steno's six postulates opened the door of understanding in scientific geology and paleontology.

The rediscovery of sharks in the Renaissance was not limited to scholars, as men of humble education also published descriptions of sharks. One of the earliest depictions of different sharks were the illustrations by Adriaen Coenen (1514–1587), the son of fisherman and a wholesaler of fish, who produced one of the oldest manuscripts illustrating whales and fishes. His crude watercolors depict mainly whales, but some depict different sharks and they are accurate enough to discern the species (Fig. 5). Coenen finished three albums of watercolors before his death. They are seldom seen by scholars, because they have only been published in "The Whale Book" (Egmond and Mason, 2003). During this period the word "shark" appeared in the English language along with one of the earliest illustrations of a shark (Jones, 1985; Castro, 2002).

The knowledge of sharks and rays increased slowly during and after the Renaissance, and the introduction of the Linnaean System of Nomenclature in 1735 marks the beginning of modern ichthyology. However, the first major, modern work on sharks and rays would not appear until the early nineteenth century when Johannes Müller and Jacob Henle (1838–1841) published the "Systematische Beschereibung der Plagiostomen," with its careful descriptions and splendid hand-colored plates (Fig. 6).

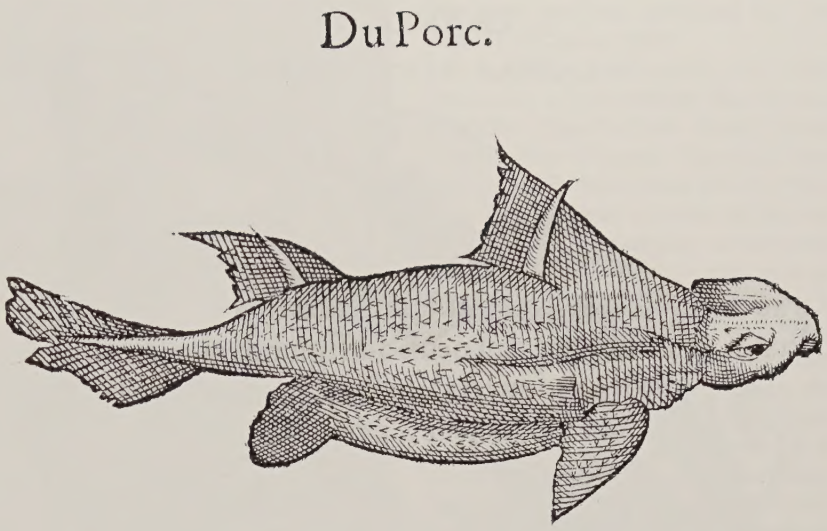

Figure 3.—Rondelet's (1558) woodcut of *Oxynotus centrina.*

Sharks in the Western Hemisphere

The first to learn about sharks in North America were the native fishermen who learned how, when, and where to catch them for food or for their oils. Archeological evidence shows that prehistoric American Indians utilized sharks widely. Extensive shark remains in Indian middens in South Florida indicate that sharks were an important food resource in prehistoric America, and that their teeth were used as cutting tools (Kozuch, 1993). Based on the dogfish spines found in the middens of the Pacific Northwest, Indians there were also catching large numbers of dogfish, but whether they were using them for oil or skin is uncertain (Ketchen, 1986). In any case, much of that early oral knowledge of sharks was lost.

Earliest Shark Encounters

Since the earliest times, sharks have presented a danger for shipwrecked sailors and for divers who regularly entered the sea. Medieval Europeans were acquainted with the small dogfishes (*Galeus* spp., *Mustelus* spp.) that were abundant along the European coasts, but there are only nominal mentions of them in the pre Renaissance literature. In general, Europeans had little contact with large elasmobranchs until after the discovery of the New World by the Spanish, so it is natural that the first accounts of large elasmobranchs came from Spanish authors.

The Spanish were familiar with small dogfish sharks which they called cazones (Castro, 2002). In the late fifteenth and the early sixteenth centuries, the early Spanish explorers first encountered the large and voracious sharks of the Caribbean, and in those days, with no fisheries preventing the sharks from reaching their allotted age and size, there must have been comparatively incredible numbers of large sharks. The Spaniards quickly distinguished the large sharks from the smaller cazones with which they

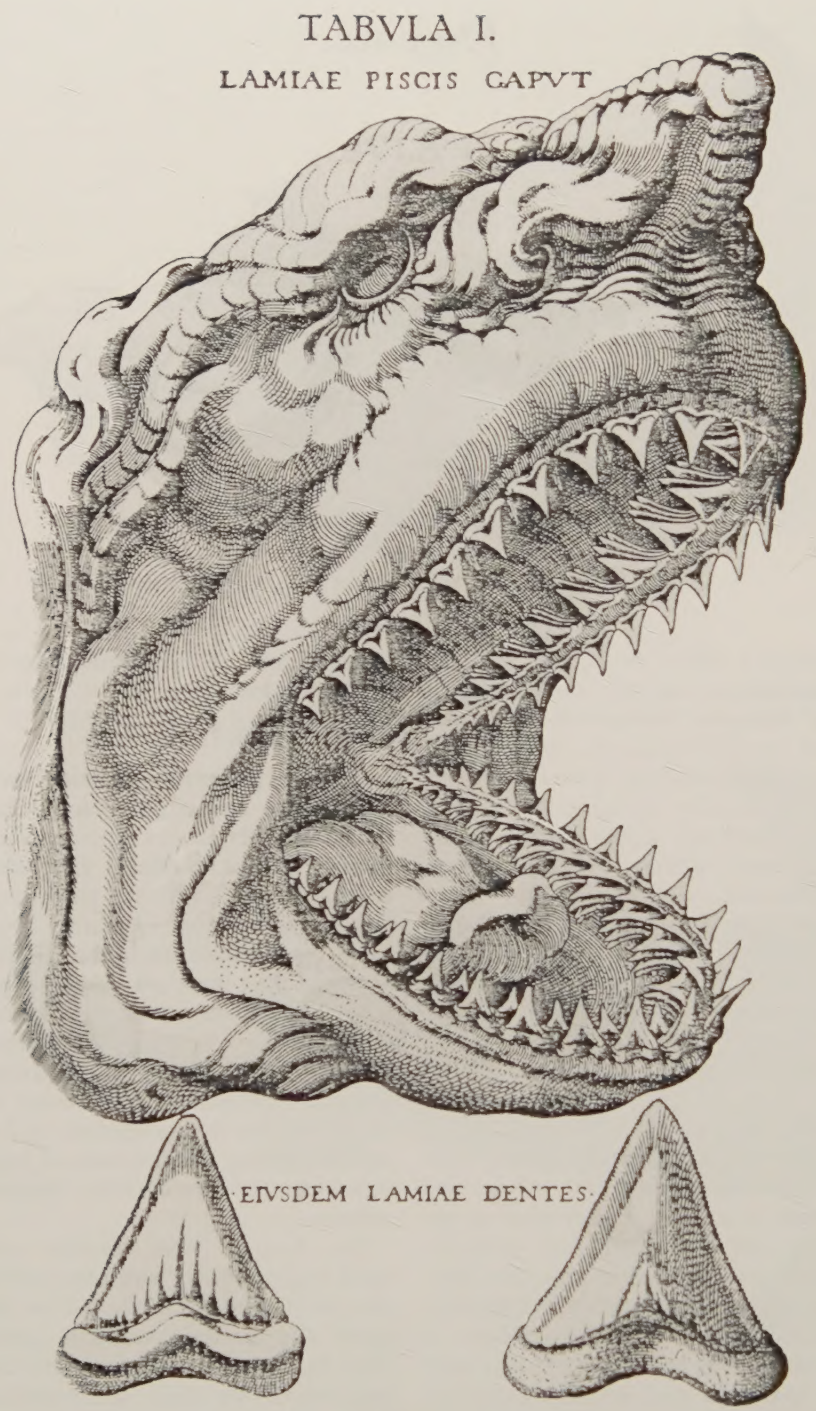

Figure 4.—Steno's 1668 drawing of the head of a White Shark, *Carcharodon carcharias.*

were familiar, and, lacking a name for them, they borrowed the Indian name, "tiburones" (singular tiburón) (Castro, 2002).

Early Natural History

Although the knowledge that the Indian tribes of the Americas had about sharks has been lost, there is evidence that some tribes were aware that sharks could be dangerous to humans. In one of the few surviving Mexican codices, the "Codex Fejérvary-Mayer" (Seler, 1902), there is a stylized figure of what is clearly a shark (Fig. 7, Seler, 1902:plate IX, No. 42). It shows an elongated fish-like creature with a mouthful of large triangular teeth, with the right number of fins for a shark, a heterocercal tail, and a human foot protruding from its mouth. It is probably a Bull Shark, *Carcharhinus leucas,* or a Tiger Shark, *Galeocerdo cuvier.* The creature is labeled "acipactli," and translated as "a swordfish." This is obviously a translation error, as the creature is certainly shark-like and lacks the identifying rostrum and homocercal tail of the swordfish, and swordfish also lack the large triangular teeth depicted in the illustration (Castro, 2002).

The first natural history of the New World was "Sumario de la Natural Historia de las Indias" written by Gonzalo Fernández de Oviedo and published in Toledo, Spain, in February 1526. In this work, Oviedo (1526:256) mentions the great diversity and number of "fishes" in the New World, but he discusses only three: tortuga (turtle), tiburón (shark), and manatí (manatee) He writes: "El segundo pescado de los tres que de suso se dijo, se llama tiburón; este es grande pescado, y muy suelto en el agua, y muy carnicero." [The second fish of the three mentioned above, is called a tiburón, this is a great fish, very quick in the water, and very much a carnivore]. De Oviedo's explanation of what the animal was called indicated that the reader was not expected to be familiar with the fish or the name.

Bartolomé de Las Casas (1484–1566) was one of early Spanish settlers in the New World, arriving in Cuba in 1502. Around 1513 he be-

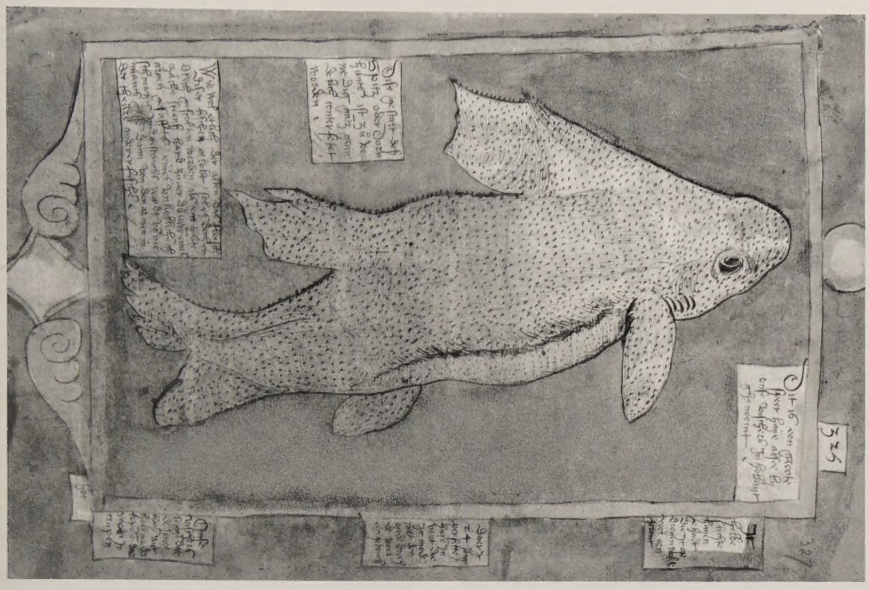

Figure 5.—Coenen' s (1585) drawing of an *Oxynotus*.

came an ordained priest (probably the first to be ordained in the Americas). In time he would become a Dominican friar and the defender of the Indians, writing extensively about the abuses and atrocities committed on them.

Returning to Spain in 1547, Las Casas joined the monastery of San Gregorio in Valladolid in 1551. In 1559 Las Casas willed the manuscript of his great work "Historia de las Indias" to the monastery, with the prohibition of publishing his work until 40 years after his death. His accounts of the atrocities committed by the Spaniards on the Indians were considered so damaging that they were not published for 350 years (Las Casas, 1951).

In a separate publication, Las Casas wrote one of the earliest descriptions of sharks from the New World. In his "Apologetica Historia Sumaria," begun in 1527, Las Casas wrote: "Hay en la mar y entran tambien en los rios unos peces de hechura de cazones ó al menos todo el cuerpo, la cabeza bota y la boca en el derecho de la barriga, con muchos dientes, que los indios llamaron tiburones..." (Las Casas, 1958:36) [There are in the sea (of Hispaniola) some fishes that also enter the rivers, built like cazones or at least their whole body, the head blunt, and the mouth in the centerline of the belly, with many teeth, that the Indians called "tiburones"].

Las Casas also penned in his Historia the first report of a shark attack on humans in the New World (Las Casas, 1951). Most of the Spaniards that came to the New World expected to become very rich in a short time. Besides searching for gold and spices, many also searched for pearls. Because many of the Indians were great divers, the Spaniards compelled their Indian slaves to dive for pearls.

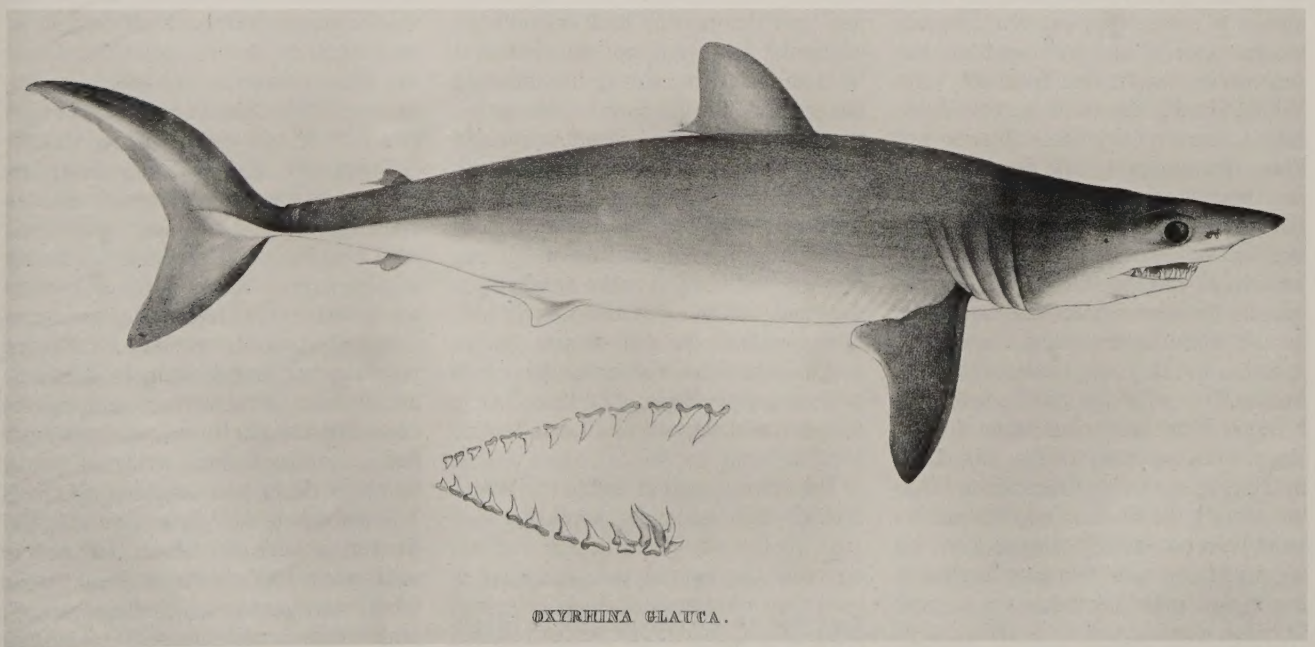

Figure 6.—Müller and Henle' s (1838–1841) depiction of a Shortfin Mako, *Isurus oxyrinchus*.

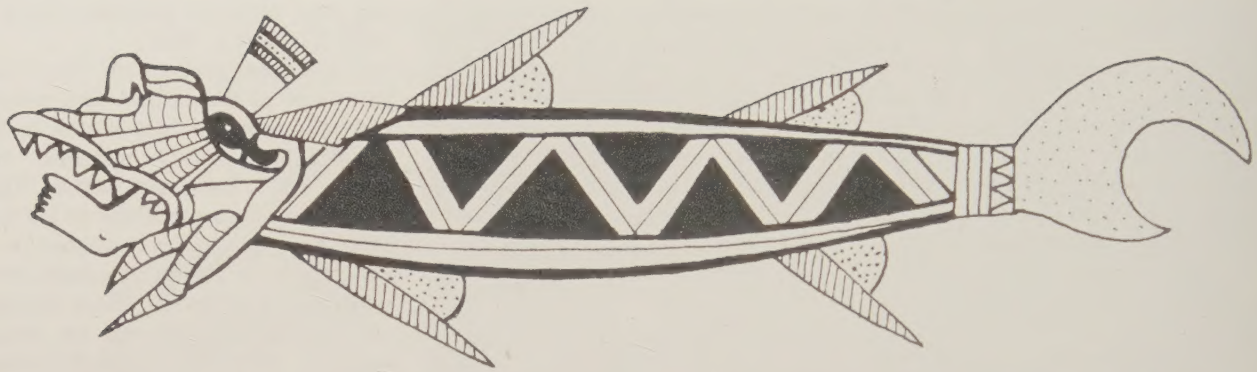

Figure 7.—Depiction of a shark with a human foot sticking out of its mouth, from Seler, 1902. Note the correct number of fins, heterocercal tail, and triangular teeth.

In the third volume of his "Historia de las Indias" (1951) Las Casas wrote: "They take them [Indians] in their canoes, which are their small boats, and a Spanish executioner [verdugo] goes with them to direct them; arriving in deep water three or four fathoms deep, he orders them to enter the water; they dive and go all the way to the bottom and there they take the oyster[4] that carry the pearls, and they fill some small nets that they carry around their necks..."

He continued, "Commonly there are two species of beasts, and even three, being very cruel, that eat men, and even horses they can tear to pieces; one species is 'tiburones,' and the second is 'marrajos' [probably the White Shark], the third is crocodiles; called 'lagartos' by those that do not know [the ignorant]. The tiburones and lagartos, which have admirable teeth, seize a man or a horse by the leg or by the arm or any other part, and taking him deep, they kill him there, and eat him on their own time; the 'marrajos' are very much larger and have great mouths, and they can swallow [a man] on the first gulp. On one occasion, it happened that an Indian, upon diving, saw a marrajo close to him, and came up fleeing up out of the water [onto the canoe]; the Spanish executioner argued with him asking why he came up so quickly without bringing anything; the Indian said that there was a great fish and that he feared it would kill him; the Spaniard forced him to return to diving and to make sure beat the Indian with a stick. The sad Indian dove, and the marrajo, that was waiting for him, charged him and swallowed him. It seems that at the beginning the Indian fought with the fish, and there was a swirl in the water for a while; the Spaniard understood that the fish had attacked the Indian, and seeing that the Indian was not returning, he killed a small dog that they had in the boat, and put it on a hook with a heavy chain, which they commonly carry for these fishes, and threw it in the water; and later the marrajo took it [the baited hook] for it was not satisfied, and the hook set in such way that it could not escape; the Spaniard feeling that the fish was hooked, gave it enough line, and slowly returned towards the beach in his canoe or boat. Jumping to the land, he called for people to help him, they landed the beast, giving blows with axes and rocks or whatever they had, and killed it, opening its belly they found the unfortunate Indian and took him out, the Indian gave two or three gasps and he died there." (My translation, from vol. 3 of Las Casas, 1951:403.)

The marrajo was probably the White Shark[5]. The name is applied today to the Mako Shark (genus *Isurus*) in many Spanish speaking countries. Both the White Shark and the Mako are lamnoid sharks with pointed noses and powerful caudal keels on the caudal peduncle and can be easily confused in the water. At the time when Las Casas and Oviedo were writing (early 1500's), Caribbean monk seals, *Monachus tropicalis*, were abundant in the West Indies. Oviedo, in vol. 2 (1535:59) wrote that "There are many seals and they are very large in the seas of these Indies, as well as among such islands, and also on the coasts of the mainland." I believe that White Sharks frequented those waters just as they frequent waters around seal and sea lion rookeries elsewhere today, whereas Mako Sharks are oceanic species that do not enter shallow waters. Oviedo, vol. 2, (1535:62) describes them in this way: "Marrajo es un animal mayor que el tiburón e más fiero, pero no tan suelto ni presto. Quieren en algo parecer a los tiburones, porque son asimesmo animales de cuero, pero como digo, son mayores...Destos he yo visto con nueve ordenes de dientes, unos en torno de otros la boca circuida. En España los hay, en los mares della, de la mesma manera, segun hombres de la mar lo dicen. [Transl: The marrajo is a larger animal than the tiburón (shark) and fiercer, but not as swift nor ready to pounce. They somewhat resemble sharks, as they are both scaleless animals, but as I said, they are bigger. Of these I have seen some

[4]The pearl oyster, *Pinctata imbricate* (MacKenzie et al., 2003).

[5]The only other shark in the area capable of swallowing a human being would be a large Tiger Shark. Oviedo's statement that the marrajo is present in Spanish waters suggests the White Shark.

with nine rows of teeth, one behind the other in the circular mouth…They are found in the seas off Spain, according to what the seamen say].

The Caribbean monk seal was subject to an indiscriminate slaughter for over 300 years and was so scarce by the 1880's that Allen (1887:2) referred to it as an "almost mythical species." It has been considered extinct since the 1950's (Kenyon, 1977). As the abundant seals were killed off, the White Shark ceased to visit the shallow coastal waters of the West Indies. The name marrajo endured, on its similar cousins, the Mako Sharks, *Isurus* spp.

Shark attacks on pearl divers continued throughout the Spanish Americas during the colonial period. Once the Indian divers (and their entire tribes) had been obliterated though disease, famine, and the Spanish cruelties, they were replaced by black slaves.

Antonio de Ulloa (Seville 1716–Cadiz 1795) governor of Louisiana and Florida, geographer, and member of the La Condamine expedition to Ecuador, traveled extensively though the Spanish Americas in the 1700's. In 1748, de Ulloa wrote "Viaje a la América Meridional," an extensive description of the places and peoples he visited. He described the pearl fishery in the many islands of the Archipelago de las Perlas, such as Isla del Rey and Taboga. Sharks were greatly feared by the pearl divers. "Sharks and tintoreras [female sharks, but usually Tiger Sharks], of monstrous size, make proper meals of the bodies of the fishermen," wrote de Ulloa (2002:173–174). "Boats carrying eighteen to twenty black divers with a foreman, more or fewer depending on the size of the boat and the number in the team, travel far from shore to places they recognize as oyster grounds and where the water depth does not exceed ten to fifteen fathoms deep."

The divers were tied to the boat by a rope and each carried a weight to allow them to get to the bottom easily and search for oysters. "The black foreman, who remains in the boats, maintains a lookout for them [sharks and mantas] and announces their presence by means of the ropes attached to each slave, so that the divers are warned, and the foreman will even enter the water with a weapon to assist in the diver's defense, but despite this precaution and help, usually some of the black divers are entombed in the maw of these fishes, some are maimed losing a leg or an arm, depending on how they are seized (De Ulloa, 2002:173, my translation).

Interestingly, the Manta, *Manta birostris*, was also "much dreaded" by the pearl divers (Jordan, 1907). Why did such a filter-feeding, gentle giant acquire such reputation? According to de Ulloa (2002), "the mantas squeeze them [the fishermen], enveloping them with their bodies or putting all their weight against them on the bottom; it seems that, not without reason, that the name manta [blanket] was given to this fishes, from its shape and properties, the shape being as extensive and big as a blanket, it has the same purpose, of enveloping the man or other animal that it catches, squeezing it in such manner, that it makes [the victim] exhale its last breath by being compressed; the form of this fish is similar to a ray, except for being incomparably larger" (de Ulloa, 2002:174, my translation).

Mantas are well known to tangle with mooring lines or boat anchor lines, and so dragging buoys or small boats for long distances. So, it is likely that one of these behemoths, swimming through the multiple lines dangling from a pearl fishing boat, could catch one of the lines in its cephalic appendages, and so pull the unfortunate diver against its ventral side, giving the appearance of enveloping the diver and dragging him to the depths, and probably forcing the crew to sever the line. Conversely, the tangled manta could follow the path of least resistance along the rope and end at the bottom pressing the diver in the manner described by de Ulloa. This is probably how the manta, plankton-feeding and gentle, acquired its earlier names of devil-ray or sea-devil, and a sinister reputation.

The Curious Naturalists

The European colonization of America brought the early naturalists (e.g., Bannister, Bartram, Wilson, Audubon). These men studied the land animals and plants, but they had little interest in sea animals which were difficult to study. Sea animals were studied when they were exploited and became economically important, and the knowledge of sharks followed this trend. Curious naturalists would not study sharks until the early twentieth century, at about the same time when sharks started to be exploited. So, to understand how knowledge of sharks was acquired in North America, one must follow the development of natural history as well as the industries that exploited sharks.

When faunistic works on fishes started to appear in the 1800's, naturalists just enumerated the species of sharks that they could discern, if any, that they had obtained from the literature, sometimes adding a few assorted facts. One of the earliest works on fishes in North America is Smith's "Natural History of the Fishes of Massachusetts" (1833) which included eight species of sharks (and four rays), most of which can clearly be identified: Smooth Dogfish, *Mustelus canis*; Spiny Dogfish, *Squalus acanthias*; White Shark, *Carcharodon carcharias*; Blue Shark, *Prionace glauca;* Common Thresher, *Alopias vulpinus*; Hammerhead Shark, *Sphyrna* sp.; and Basking Shark, *Cetorhinus maximus*. Smith's accounts are generally short and fanciful, except for that of the White Shark which repeats the dreadful accounts of its voracity and attacks on humans so common to the White Shark literature.

DeKay (1842) gave more comprehensive taxonomic descriptions of 13 sharks (Fig. 8) in his book on the fauna of New York, but there was little else in the descriptions. Storer (1845), in his "A Synopsis of the Fishes of North America," included 14 species in his Squalidae (which included the genus *Pristis*). He gave but a brief description of the sharks, stating "With most

Figure 8.—*Mustelus canis* (DeKay, 1842).

of the species found out of the waters of Massachusetts, my acquaintance is but slight. Many of them I have had no opportunities of examining" (Storer, 1845:254). The Civil War and the hard economic times that followed prevented any further works on American sharks until early in the next century.

At the beginning of the twentieth century, most ichthyologists had little interest in sharks. Ichthyologists were trained to identify fishes, and usually cared little about their biology, except for a few species of commercial importance. And ichthyologists identified fishes using meristic traits such as scale or spine counts, skeletal bone structures, etc. Sharks did not have commercial importance and none of the morphological characteristics that ichthyologists liked to use for identification. So, ichthyologists generally ignored sharks. David Starr Jordan (1907), the dean of American ichthyologists, covered the entire elasmobranchs in 37 of the 789 pages of his comprehensive popular work "Fishes." In a prefatory note to the second edition of his book, Jordan (1925) wrote "the writer has tried to compress all that an educated man is likely to know, or care to know about fishes." The implication was clear, ichthyologists, ergo, people, had little interest in sharks.

Despite the ichthyologists's general lack of interest in sharks, in the early twentieth century, a few works on sharks were published that have not been surpassed in usefulness and beauty. The first of these works was "The Normal Plates of the Development of *Squalus acanthias*" by R. E. Scammon (1911), of the Harvard Medical School. Scammon illustrated the entire development of the Spiny Dogfish, with excellent drawings of both whole embryos and cross and sagittal sections (Fig. 9). It remains today as the most complete reference to the normal developmental stages of sharks. This work was part of a German series ("Normentlafen zur entwicklunsgeschichte der wirbeltiere") on the embryonic development of animals.

The first American treatise dedicated to elasmobranchs, "The Plagiostomia," was done by Samuel Garman (1913), of the Museum of Comparative Zoology at Harvard College. This work covered all the species then known from throughout the world. The work is strictly taxonomic, but the illustrations of sharks, rays, and anatomical details are splendid (Fig. 10). There is almost no biological information about species because such was the lack of knowledge of the natural history of sharks at the time.

The only attempt to understand the behavior of sharks in the early twentieth century was by G. H. Parker (1914), who carried out a series of experiments to understand how dogfish used their sense of smell. In the following decades, sharks would acquire increasing economic importance and our knowledge about them would expand dramatically, although the birth of shark biology (and not just shark taxonomy) was still decades away.

Bashford Dean

The most significant works on sharks of the early twentieth century resulted from the work of Bashford Dean (1867–1928), a scholar with diverse interests ranging from archaic fishes to medieval body armor (Gregory, 1930–1933). He was professor of vertebrate zoology at Columbia University, curator of recent and fossil fishes at the American Museum

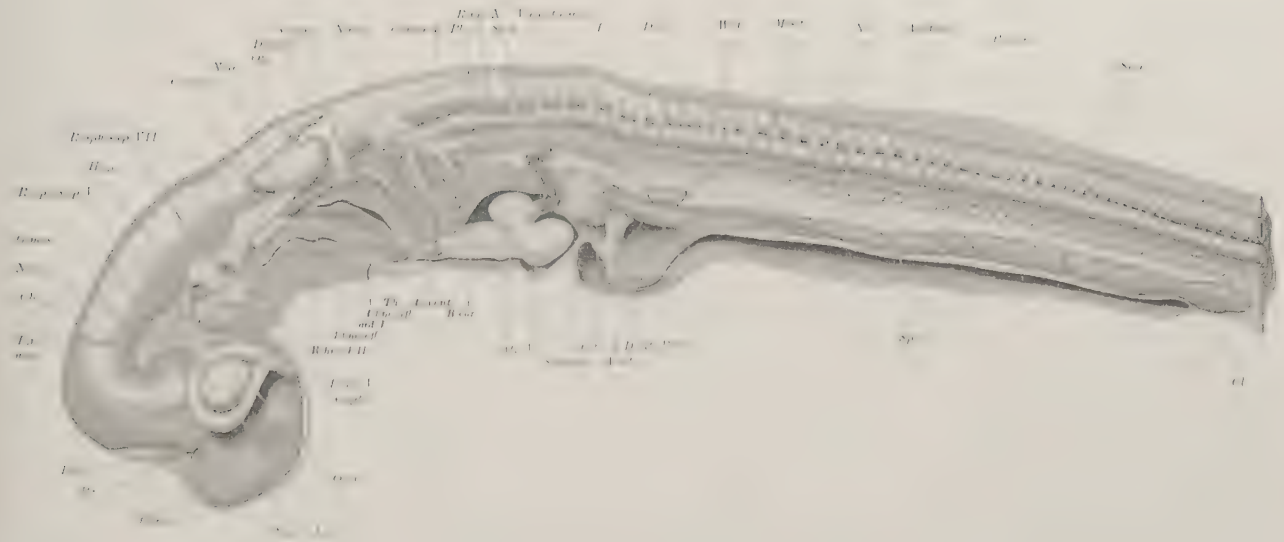

Figure 9.—*Squalus acanthias*: 15 mm embryo, sagittal section (Scammon, 1911).

of Natural History, and an expert and collector of medieval armor. Entering the College of the City of New York before he was fourteen years old, he graduated with high honors in the class of 1886. Later he entered Columbia University as a graduate student in geology and biology, obtaining his doctorate in 1891.

At a time when ichthyologists were simply trained to identify fishes, often ignoring everything else about them while becoming obsessed with trivia of the nomenclature, Bashford Dean studied the embryology, anatomy, and paleontology of fishes, and never lost an opportunity to watch the behavior, spawning, or nesting of fishes. In 1895, at the age of 28, after some five years of work in ichthyology, he published his notable textbook, "Fishes, Living and Fossil," a unique work that synthesized embryology, comparative anatomy, and paleontology of fishes. His subsequent work "The Chimaeroid Fishes and Their Development" (1906) continued his pattern of describing the embryology, anatomy, and paleontology of the fishes he studied.

Most people consider that Dean's magnum opus was the three-volume "Bibliography of Fishes" (Dean, 1962; first published in 1917, the last volume issued in 1923), covering the entire literature of both living and fossil fishes. For this great work, which took over thirty-three years to complete, the National Academy of Sciences awarded him the Daniel Giraud Elliot medal in 1923. This work was reissued in 1962 because it remains the most useful source for the pre 1914 literature on fishes. However, I consider that Dean's greatest contribution was in the unfinished drawings and notes he left behind, for these engendered some comprehensive works whose beauty has never been surpassed.

The discovery of the Frill Shark, *Chlamydoselachus anguineus*, in 1884 (Garman, 1885–1886) caught Dean's attention and in the early 1900's, he traveled to Japan and secured 39 specimens (Gudger and Smith, 1933). Dean studied the Frill Shark and the Japanese Horn Shark, *Heterodontus japonicas*, for many years, making exquisite drawings of developing embryos of both species. He also provided other scholars with anatomical material that resulted in several published works (e.g., "The Cranial Anatomy of *Chlamydoselachus anguineus*" (Allis, Jr., 1923; Fig. 11). Unfortunately, Dean died in 1928 before finishing his studies.

After his death, Eugene W. Gudger, also of the American Museum of Natural History, and Bertram G. Smith, Professor of Anatomy at New York University, used Dean's materials and notes to prepare a series of monographs on the Frill Shark and the Japanese Horn Shark, which were published in the Bashford Dean Memorial volume. Those dedicated to the Frill Shark are: "The Natural History of the Frilled Shark *Chlamydoselachus anguineus*" (Gudger and Smith, 1933); "The Anatomy of the Frilled Shark *Chlamydoselachus anguineus* Garman" (Smith, 1937); and "The Breeding Habits, Reproductive Organs, and External Embryonic Development of *Chlamydoselachus* Based on Notes and Drawings Left by Bashford Dean" (Gudger, 1940). Dean's work on the Japanese Horn Shark was published in "The Heterodontid Sharks: Their Natural History, and the External Development of *Heterodontus (Cestracion) japonicus* Based on Notes and Drawings by Bashford Dean" (Smith, 1942; Fig. 12). The resulting monographs are splendid, comprehensive works seldom equaled in the study of sharks.

Eugene Willis Gudger

Eugene Willis Gudger (1866–1956) was the first American ichthyologist that can be considered a true naturalist and the first to study the biology of

Figure. 10.—*Mustelus henlei* and *Carcharodon carcharias* (Garman, 1913).

elasmobranchs. Gudger, who received his Ph.D. degree from Johns Hopkins University in 1905, wrote more than 300 papers on subjects ranging from fireflies and fishing spiders, to jaguars and sharks. Unlike most of his fellow ichthyologists who were interested only in identifying and naming fishes, the eclectic Gudger wrote numerous papers about the habits of many bony fishes and sharks. Many of his articles were published in popular natural history magazines. He was Professor of Biology at the North Carolina College for Women (1905–1919). In 1919, at the request of the American Museum of Natural History, he became the editor of the third volume of "A Bibliography of Fishes" by Bashford Dean (1962). Later he edited the "Bashford Dean Memorial Volume" (referenced earlier), and authored or coauthored two of the articles. He remained at the Museum as an assistant curator and later as honorary associate in ichthyology. He was the first to conduct field studies of numerous elasmobranchs, and wrote papers on the feeding habits of the Great Hammerhead, *Sphyrna mokarran* (Gudger, 1907), natural history notes on the sharks and rays of Beaufort, North Carolina (Gudger, 1912), and the feeding habits of the Tiger Shark, *Galeocerdo cuvier* (Gudger, 1948a, 1948b, 1949). His monograph (Gudger, 1914) on the Spotted Eagle Ray, *Aetobatus narinari*, remains the source document on the species.

Gudger had a lifetime preoccupation with the Whale Shark, *Rhincodon typus*, and wrote more than 40 papers on the species. Gudger was able to examine only one Whale Shark in his life (Fire Island, N.Y., 1935), so many of his papers are just second-hand capture records for various localities. Although in 1952 some believed that Whale Sharks were oviparous, Gudger (1952) wrote "One could not conceive such a giant laying eggs." Time would prove him correct, but it would take more than four decades for proof to be obtained (Castro, 2011). He also accurately anticipated that Whale Sharks

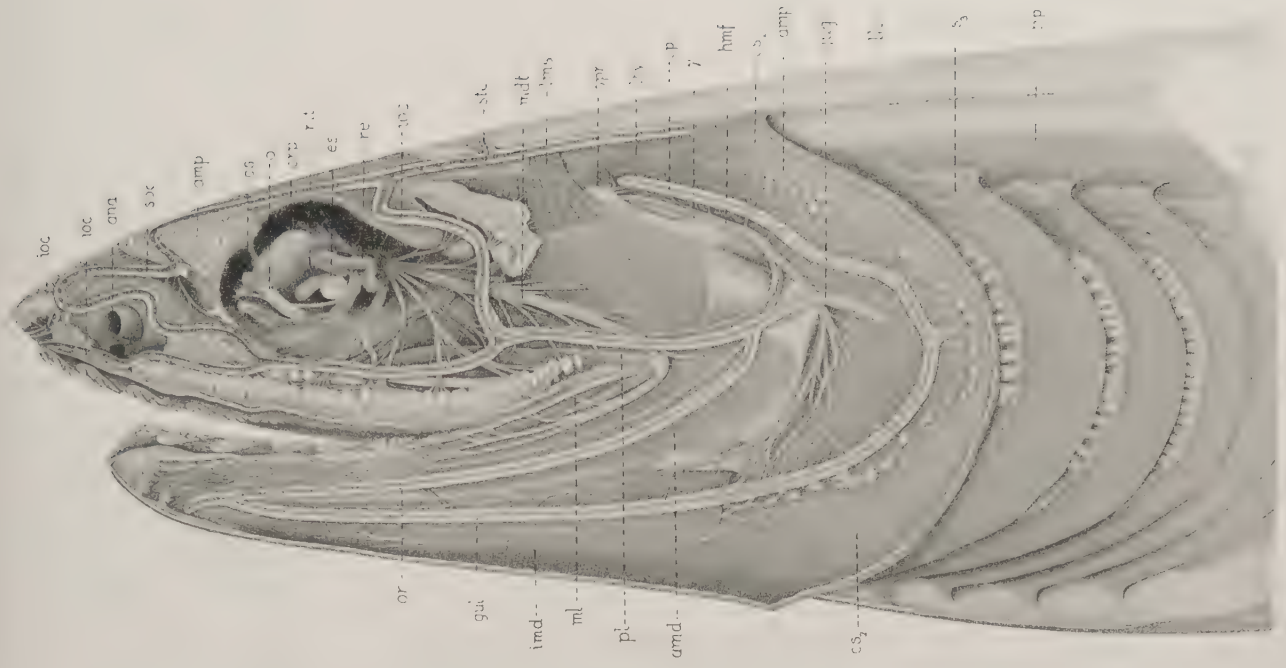

Figure 11.—*Chlamydoselachus*: Lateral view of head, with dermis and eyeball removed, by J. Nomura (Allis, 1923).

grew rapidly, long before any growth data were available.

Gudger also wrote papers on the history of ichthyology, ranging from Pliny's "Historia Naturalis" to the Renaissance ichthyologists and their discoveries (Gudger, 1924, 1934, 1950). There is a partial "Bibliography of Dr. E. W. Gudger's Contributions to the History of Ichthyology" (Gudger, 1951), with an editorial note by historian George Sarton promising a "complete bibliography which will eventually be published in a journal devoted to ichthyology or natural history." (Gudger, 1951:237). To my knowledge, such a bibliography has never been published.

The Dogfish Oil Industry

English colonists in America had no tradition of using sharks as food, though shark liver oil and skins were utilized through the colonial period. John Lawson, who explored the Carolinas around 1700, summed up the colonist's attitude and use of sharks in his "A New Voyage to Carolina" (1709:155): "Their Livers make good Oil to dress Leather withal; the Bones in their head are said to hasten the Birth, and ease the Stone, by bringing it away…Their meat is eaten in scarce times; but I never could away with it, though a great lover of fish...The dogfish are a small sort of the Shark Kind; and are caught with Hook and Line, fishing for Drums. They say, they are good Meat; but we have so many other sorts of Delicate Fish, that I shall hardly ever make Tryal of what they are."

Throughout the nineteenth century, the Spiny Dogfish was the only shark species utilized in any degree on both coasts. It was fished for its liver oil, which was used as a lubricant and for lighting and tanning, and for its skin which was used as an abrasive. Dogfish oil was considered "quite superior to whale oil" for lighting purposes, and when properly refined, it was "second only to sperm oil" (Swan, 1870).

Dogfish oil was used extensively in the tanning industry for the currying of leather. Tressler (1923) stated that its most important use in the early twentieth century was in the tanning industry. Dogfish oil was also used as a lubricant in many tools and mills of the period. It was also used for medicinal purposes due to its vitamin A content.

Smith (1833), in his "Natural History of the Fishes of Massachusetts," wrote that the skin of the dogfish "when dry, is used by cabinet makers for polishing wood, and by surgical instrument makers, for covering cases." He also summed up the concern about dogfish of his time: "It is a spiteful, voracious, cartilaginous shark,—very muscular, and the eternal enemy of cod,—getting possession of the feeding ground, some seasons, to the great loss of the fishermen. In 1831, they were so uncommonly numerous, that the cod-fishery was attended with immense loss. The dog-fish is familiarly known along the entire coast of the United States, that is it quite unnecessary to be minute in the description" (Smith, 1833:82.).

Although despised by the cod fishermen, the dogfish became an important fishery in New England during the early nineteenth century. Goode (1884:674) quoted a Massachusetts

Figure 12.—Development of *Heterodontus japonicas* (Smith, 1942).

fisherman stating that: "When I first began to go fishing, in 1810 to 1820, the Dogfish fishery was considered one of the most valuable fisheries that we had around the shore. They appeared here in the spring and were very plenty, and would last a day or two and then all would be gone. Then you would not see a Dogfish again all summer; but about the 10th, or middle of September, they came to us again returning south, They would stay into November, and during that time the fishermen would get—a man and a boy—all the way from eight, ten, to fifteen barrels of oil." Goode also added that "In addition to the oil yielded by these little Sharks, the skin is of considerable value, and will doubtless in future be more highly prized than it is at present. It is used by the fishermen to polish their metallic mackerel-jigs and sometimes in polishing the fancy wood-work shipboard."

The dogfish also became an important industry on the Pacific Northwest coast. The Indian tribes of the area had been using dogfish oil and skin for centuries. James G. Swan[6], one of the early settlers in the Washington Territory, wrote in his ethnographic monograph on the Makah Indians (Swan, 1869:29): "The dogfish (yá-cha) *Acanthias suckleyi*, is taken in great quantities for the sake of the oil contained in the liver, which forms the principal article of traffic between these Indians and the whites...The method of extracting as practiced by the Makahs is to collect the livers, which are put into a tub and kept until a considerable quantity has accumulated. They are then put in to iron pots, and set to simmer near the fire; or else hot stones are placed among them and they are cooked by the heat until all the oil is extracted, which is then carefully skimmed off and stored in receptacles made of paunches and intestines of whales, fish or seals. In the fall of the year the flesh of the dogfish contains a considerable proportion of oil, which at other times it does not appear to possess; this is extracted in the following manner: When the livers are taken out, the head and backbone are also removed, and the rest of the body, being first slightly dried in the smoke, is steamed on hot stones till it is thoroughly cooked. It is then put into little baskets made for the purpose, of soft cedar bark, and rolled and squeezed till all the liquid is extracted. This in color resembles dirty milk. It is boiled and allowed to cool and settle, and the oil is then skimmed off. After the oil is extracted, the flesh is washed in fresh water and again squeezed in the baskets and in this state it is eaten by the Indians when other food is scarce. But dogfish is seldom tasted by the Makah and never until all the oil has been thoroughly removed. The oil has a nauseous taste and it is not relished by these Indians, who are epicures in their way, and prefer the oil of whales and seals" (Swan, 1869:29).

Gedosch (1968:100), wrote an interesting history of the dogfish oil industry in the Washington Territory and stated that "production and trade in dogfish oil was common to the Makah of Cape Flattery, the Layouts, Intimates, the Notches of British Columbia, the tribes inhabiting the lands fronting on Puget Sound, and, to a lesser extent, those living on the coast... The Canadian Indians traded dogfish oil to the Makah and the latter sold the oil to the white men."

When New England lumbermen moved to the Pacific Northwest in the 1850's, they were accustomed to using fish oil as lubricant, and they were familiar with the Spiny Dogfish and its oil (Gedosch, 1968). Thus, the lumber industry lent new impetus to the local dogfish oil production, and by the late 1800's and the early 1900's there was an active fishery for Spiny Dogfish in the Canadian Pacific Northwest (Ketchen, 1986). Oil was extracted from the liver for lubrication and lighting, and the flesh was used for fertilizer.

By the mid 1880's, coal oil and petroleum products appeared in the market, and they were cheaper than dogfish oil by 5–10 cents per gallon (Gedosch, 1968). There was also competition from Icelandic and Japanese dogfish oils. The State of Washington dogfish oil industry still existed in 1890, when 50,000 gallons of oil were produced. After 1892, the annual reports issued by the state fish commissioner do not mention oil extraction, probably because there was little or no production (Gedosch, 1968). It would take nearly four decades before the shark liver-oil industry would revive again.

The Ocean Leather Company

The large scale utilization of sharks in the United States begins with The Ocean Leather Company[7] during the early part of the twentieth century. Businessman Alfred Ehrenreich had been exploring the utilization of sea animals (sharks, rays, porpoises, small whales) for commercial purposes. Ehrenreich contacted the Bendixon brothers of Copenhagen, Denmark, who had patented a method of tanning the hides of sharks and whales. At Ehrenreich's request one of the Bendixon brothers came to the United States to arrange for the utilization of their patents in the production of leather from sharks and cetaceans.

In the spring of 1917, Ehrenreich and Bendixon, along with a group of stockholders, launched the Ocean Leather Company to handle the American patent rights and products of the

[6]James G. Swan (1818–1900), arrived in the Washington Territory in 1852. He led an interesting and colorful life, being an oysterman, judge, diarist, reservation schoolteacher, and ethnographer (among his many occupations). He lived with the Indians for many years and learned their culture and languages. Among the works of this prolific writer are two classic monographs on the Makah and Haidah Indians which were published by the Smithsonian Institution. For a biography of this interesting and prolific man, see McDonald (1972).

[7]Much of the information in this section was obtained from a manuscript titled "Report to A. Iselin & Co. on the Ocean Leather Company, Inc.," produced by The Industrial Company, of Boston, Mass., and dated May 1921. The Industrial Company had been requested by potential investors to investigate whether the leather company was "engaged in a sound business or commercial development of promise" and if the answer was affirmative, to formulate a profitable business plan. The manuscript is currently in the author's possession, and a copy will be placed at the library at the Southeast Fisheries Science Center, Miami, Fla. Mention of trade names or commercial firms does not imply endorsement by the National Marine Fisheries Service, NOAA.

Danish tanning patents, as well as to investigate other potential products from sea animals (primarily sharks) such as oil, fertilizer, fins, etc. The Ocean Leather Company was incorporated on 18 April 1917, in Delaware, and it started with a small experimental tannery on Tyler Street, Newark, N.J. This small facility was insufficiently equipped for attempting the necessary tanning experiments, and it was not until the summer of 1918 that the tannery was properly equipped for work. At that time, the company was unable to produce marketable shark leather because of the inability to remove the dermal denticles of the shark hides, which were described by Ehrenreich as being "hard as steel."

In a letter written by Ehrenreich, dated 18 January 1920 (Industrial Company manuscript, 1921), to prospective investors, he states that "We were unable to produce a marketable leather because principally of our inability to remove the shagreen, which is dermal denticle upon the skin of the shark, hard as steel, and which resisted every effort to remove by mechanical devices, although experiments were tried for months and months, using every sort of device known or which we could invent, and using every known friction agent, from sand paper to the shark skin itself. All the skins tried out along these lines were ruined. Experiments were then conducted along chemical lines and various processes were thought to have solved the problem and were patented, only to be discarded. Finally the problem was solved in 1919, but after the solution of the difficulty, further experiments were necessary in order to perfect the process."

The solutions to the denticle removal problem came from two sources. Theodore H. Kohler (1925) developed and patented a process for removing the denticles from vegetable-tanned shark skin using hydrochloric acid, while Allen Rogers developed and patented several processes for removing the denticles from fresh hides using a hydrochloric acid and salt solution (Rogers, 1920a).

Allen Rogers was one of the foremost experts in leather manufacture and tanning in the early part of the twentieth century. He was born in Hampton, Maine, on 22 May 1876, and graduated from the University of Maine in 1897 with a B.S. degree in chemistry. He also received an M.S. degree from his alma mater, and in 1902 he received a Ph.D. degree from the University of Pennsylvania.

Rogers worked both in industry and academia to solve problems of the leather industry, obtaining several patents for industrial processes. He did much pioneering work on the manufacture of leather from marine animals, and eventually became one of the foremost experts in leather and leather tanning.

During World War I Rogers volunteered for military duty and was commissioned as a Major in the Chemical Warfare Service. In 1920 Rogers' paper "Industrial Uses for the Shark and Porpoise" received the Grasseli Medal, an annual award for the paper, presented before the New York Section of the Society of Chemical Industry, that offered the most useful suggestions in applied chemistry (Bogert, 1920).

Through his work in leather processing, Rogers became acquainted with Alfred Ehrenreich. In an Ocean Leather Company document dated 31 December 1920, Rogers is listed as one of seven directors of the company (Industrial Company ms., 1921).

With the Rogers patents at hand, the perfection of the tanning and dearmoring processes, and the prospect of a monopoly in shark leather processing, the company obtained the needed capital to expand. In 1921, Alfred Ehrenreich wrote "Application is now pending for a patent for 'de-armored shark skin' as a manufactured article, which our patent attorney, Mr. Albert F. Nathan, believes it will be granted, and, if granted, he advises that the patent will give us a monopoly upon our product with whatever process infringers seek to operate, even though by a different process than the one discovered by us (Industrial Company ms., 1921). Additional revenues would come from the meat, fins, oil, and fertilizer production.

In early 1919, work was started on a plant for "the reduction of sharks, and the like, to fertilizer, oil, fins, hides, etc." at Morehead City, N.C. The plant was operational by fall. Lack of funds prevented the company from hiring a competent supervisory engineer and obtaining sufficient boats. In 1920-21, Ocean Leather sold stock and raised capital for expansion.

In the early 1920's, despite the experience with whales, fur seals, and many other sea animals, the sea was still considered an inexhaustible resource. Company literature cited "Unlimited supply of raw materials provided by nature at no cost." Undoubtedly, the stocks of sharks in North America in 1920 must have been immense. The Ocean Leather Company management quoted freely from the over optimistic predictions of the savants of the time. Ichthyologist John Treadwell Nichols, of the American Museum of Natural History, had estimated "that not less than 1,250,000 shark per diem pass in and out of coastal channels between Cape Hatteras and Cape San Roque."[7] Consequently, the projections for the numbers of sharks to be processed at the plants were quite optimistic. Rogers (1920a:9) wrote that "the Ocean Leather Company alone expect [sic] to bring their catch to 1000 sharks per day, and with an estimated catch by other fishermen of 1000 daily we would have 2000 sharks averaging 100 lb., representing a supply of edible material to the amount of 75,000,000 lb annually." A company prospectus for a stock offer (probably ca. 1920) predicted a daily total income of $17,076.00 based on a daily catch of 1,000 sharks and 100 sea mammals.

A second processing plant was started in 1921 at Sanibel Island, Fla. By 1921, the Newark tannery was processing about a thousand skins every week (Rogers, 1920b). The company would continue to grow through the 1930's, but not to the rosy expectations of its founders, despite enjoying a mo-

nopoly in shark leather processing. In a letter, dated 18 November 1937[8], to a Mr. Bolton who had inquired to the Bass Biological Laboratory about the market for shark skins, Stewart Springer replied that "So far the industry has apparently not been able to get a sufficient quantity of hides. I doubt whether an increase in the amount offered for hides would produce more. The Ocean Leather Corporation has been paying 70¢ for a 36" hide to $5.40 for a 136" hide. Nurse sharks bring a slightly higher price in proportion. There are average sizes for the various species. From the point of view of the catcher it is not worth while to work with sharks less than 8 feet long. These produce a hide about 70 inches long...The Ocean Leather Corporation of Newark, New Jersey has a practical monopoly as far as I know."

The Ocean Leather Company enjoyed a long monopoly on the shark leather industry for many years. A letter from Stewart Springer at the Bass Laboratory, dated 26 July 1940[8], addressed to a Louisiana man who was asking about the marketing condition for shark products, reads as follows: "It is unfortunate but marketing conditions for shark products are not so good. I think that Ocean Leather Corporation of 48 Garden Street, Newark, New Jersey still buys hides and I think that they will handle also fins, oil, and teeth on consignment as brokers. This company has a practical control of the shark leather business and I know of no other reliable large purchaser of shark products. A Florida company, Shark Industries, Inc. at Hollywood, Florida was buying oil from the livers but I think their demand is at present much reduced."

The shark fishing industry expanded in the late 1930's, when Charles L. Mooney established Shark Fisheries, Inc. in Port Salerno, Fla., to catch sharks in the St. Lucie River and inlet, and sell their oil and the skins (the skins going to Ocean Leather). In the early 1940's, Robert M. French, who had started Shark Industries Inc. in Hialeah, Fla., acquired the Port Salerno plant from Mooney. At about this time, Stewart Springer (see below) became associated with Shark Industries, Inc., and a 1944 paper titled "Vitamin A and Shark Liver Oils" by Springer and P. M. French gives their affiliation as Shark Industries, Inc., Hialeah, Florida." In 1944, Shark Industries, Inc., was bought by the Borden Company and became the Shark Industries Division of the Borden Company, retaining R. M. French as its chief executive. Springer would work for that company as a production manager from 1947 to 1949.

Little is known about the activities or catches of the Ocean Leather Company during the early years. According to Springer (1952) no record of shark catches existed prior to 1938, and R. M. French was responsible for establishing a data collection program then. What little is known about catches was published by Springer (1952). The Ocean Leather Company lasted until 1964, when it was taken over by the Dreher Leather Company. This company, founded in 1930 by Adolph Dreher, a German immigrant, had become one of the largest leather manufacturers and importers in the United States.

The Bass Biological Laboratory

In 1932, John F. Bass, Jr., founded the Bass Biological Laboratory in Englewood, Fla., because, according to the brochure printed for the inauguration, "there was no year 'round collecting station in the eastern and midwestern United States south of Beaufort, North Carolina...[and] that it would be advantageous to have such a field laboratory located in Florida near the subtropical belt." Its purpose was "to furnish research facilities to investigators in biological fields, where the fauna, flora and climate play an important role in the problem under observation."

Much of what was learned about sharks in the decade of the 1930's in the United States was learned at the Bass Marine Laboratory. In the 1930's, Englewood was a small town of some 200 souls in the splendid isolation of rural Florida of that era. Venice was the closest town and had the closest train station providing access and supply routes for the laboratory. The laboratory facilities were granted to faculty members of colleges, universities, and other institutions. A charge of one dollar per day was assessed to researchers to pay for laboratory maintenance.

The laboratory had a profit-making subsidiary, the Zoological Research Supply Company, a biological supply company that sold live and preserved specimens to researchers and universities. In turn, this company had a department called the Genuine Shark Products Company that dealt in products such as shark hides, shark oil, and shark-teeth jewelry.

In 1936 John Bass hired Stewart Springer (1906–1991) to be collector, specimen preparer, and guide for the scientists visiting the laboratory. Springer had attended Butler College in Indiana for two years before dropping out. He spent a year as a chemistry technician before heading to Biloxi, Miss., where he spent several years working as a commercial fisherman and a specimen collector. Springer was a keen naturalist who had a great interest in terrestrial creatures, but his experiences fishing off Biloxi and Englewood caused his interests to shift to marine animals, especially sharks.

In a letter, dated 22 August 1939[8], to Charles Breder at the New York Aquarium, referring to a recent visit to the area, Springer wrote: "I did spend a full day with the hammerheads at the National Museum and I am very much interested in seeing more from the New York area. The beasts fall into five categories which may eventually be considered of generic order....I suppose that I will be able to sort them out sometime."

At the Bass Laboratory, Springer (1938) wrote this first paper on sharks, titled "Notes on the Sharks of Florida," basically a field guide to the Florida sharks. It won him the Achievement Medal of the Florida Academy of Sciences for 1938. Six other papers would

[8]Bass Biological Laboratory Collections, Library and Archives, Mote Marine Laboratory, Sarasota, Fla.

follow: a report of a Great White Shark from Florida (Springer, 1939a), on the egg case of the Texas Skate (Springer, 1939b), on two new species of *Mustelus* (Springer, 1939c), on three new species of the genus *Sphyrna* (Springer, 1940a), on new hammerhead species (Springer, 1940b), and one on the sex ratios and seasonal distribution of Florida sharks (Springer, 1940c). In time, the self-taught Springer would become one of the most knowledgeable shark biologists, authoring more than 70 papers, mainly on shark biology or shark behavior.

John F. Bass, Jr., died in December 1939, and the laboratory entered a slow decline. Springer left in 1940, moving to Islamorada in the Florida Keys, where he managed Florida Marine Products, a commercial shark fishing operation. At this time, vitamin A obtained from shark liver oil could be a profitable operation.

The Shark Liver Oil Fishery, 1938–1948

The curative properties of cod liver oil and shark liver oil were known long before vitamins were identified and their therapeutic properties were ascertained. Although cod liver oil was preferred, shark liver oil was a ready substitute where cod liver oil was unobtainable. George Suckley (1830–1869) was a physician and naturalist who explored the Washington and Oregon Territories with the Pacific Railroad Surveys in the 1850's. His "Natural History of the Washington Territory and Oregon" (Cooper and Suckley, 1859) described many of the animals he encountered there, including the Pacific Spiny Dogfish, which was named *Acanthias suckleyi* (now *Squalus suckleyi*) in his honor by Girard (1855).

In the above report, Suckley wrote: "The present dog-fish is found abundantly in the waters of Puget Sound, and at certain seasons of the year repairs in vast numbers to the more shallow bays and flats off the mouths of its affluent streams. They attain, when adult, an average size of about three and a half or four feet; they are voracious fish, readily caught with hook and line, and are not infrequently taken by the natives with spears; their livers are large and very fat, the oil furnished by them being highly prized by the natives. It is for this latter that they are generally taken. The whites get much of their oil in trade, and use it for all purposes to which whale oil is applied. I have been assured by an intelligent oil refiner that the oil of this fish, when properly refined, is of a very excellent quality. I have used when *fresh*, as a substitute for cod-liver-oil, as a medicine for consumptive patients. It seemed efficacious, and, in one or two cases, where procurement of the latter was impossible, I was led to believe that it saved the lives of those who have taken it. It was given, with alcoholic liquors, in doses, commencing at two teaspoonfuls, increased gradually to a wine glass full, three times a day" (Cooper and Suckley, 1859:367).

Cod liver oil remained a medical staple and a source of vitamins A and D into the twentieth century. Although a cod liver oil industry had existed in the United States, it had never assumed important proportions. In 1921, only 6,015 gallons of medicinal cod liver oil were produced, and all this oil was being produced, in Massachusetts and Maine, and, shark liver oil was being manufactured only in North Carolina, in connection with the shark leather industry (Tressler, 1923). In the early 1920's, most of the cod and shark liver oils used in the United States were imported, and the main producers of cod liver oil in the world were Norway (1,318,922 gal. in 1920) and Iceland (513,160 gal. in 1922), with Newfoundland, Canada, Scotland, and Japan producing smaller quantities. Iceland was also a producer of shark liver oil (Tressler, 1923)

In California, prior to 1937, a small shark fishery existed in California, based on the Soupfin (or Tope) Shark, *Galeorhinus galeus*. It supplied a limited local demand for fresh shark fillets and for reduction into poultry feed. Most sharks were caught incidentally to other fisheries and were generally considered worthless. In 1937, it was discovered that the liver of the Soupfin Shark was the richest source of vitamin A available in commercial quantities (Ripley, 1946). Vitamin A was generally obtained from cod liver oil, usually imported from Europe, and the outbreak of World War II in 1938 interrupted those shipments. The discovery of the potency of shark liver oil and coupled with the curtailment of supplies set up a new market for Soupfin Sharks in California, and an intensive fishery soon developed. In one year the California shark fishery skyrocketed from minor to major status (Byers, 1940). According to Ripley (1946), "The fabulous prices offered for soupfin received much publicity. No mention was made of the difficulties involved in the taking of this 'gold.' Such propaganda influenced the gullible of all walks of life to leave their occupations and invest their time and money in the new strike[9]...For a brief period almost anything that would float was used for shark fishing" (Ripley, 1946:9). "Every soupfin brought aboard was the equivalent of $50 hauled out of the sea" (Roedel and Ripley, 1950:24), and so the fishery soon took the aspects of a bonanza (Ripley, 1946). By 1939 the American shark leather fishery had transformed into the shark liver oil fishery of the early 1940's, encompassing both coasts.

On the west coast, the fishery grew from California to Washington. By 1939 "a motley assortment of about 600 boats were avidly searching for soupfin up and down the coast of California." (Ripley, 1946:9). By 1941 a similar fishery for the Soupfin Shark had developed in Oregon (Westrheim, 1950). This fishery also targeted the Spiny Dogfish along the coast of Oregon and Washington. The liver of the dogfish was a much lower potency (or the amount of vitamin A in it) than that of the Soupfin Shark. Brocklesby (1927) reported that the liver oil of the dogfish, *Squalus sucklii* [suckleyi],

[9]For an excellent novella that describes shark fishing during the heyday of the California fishery, read "The Forty Fathom Bank" by Les Galloway (1994).

was a potent source of vitamin A, while Brocklesby (1929) determined that the potency of vitamin D varied in samples from different localities from less than 10% to about 30% of the potency of medicinal cod liver oil. A valuable fishery soon developed because dogfish were available in great quantities (Ripley, 1946).

On the east coast, the shark fishery of the 1940's was based in Florida and was small, seldom involving more than five boats in Florida and a total of 16 in the southeastern states (Springer, 1952). This fishery targeted larger sharks of the genera *Carcharhinus* and *Sphyrna*. An east coast liver oil fishery for the Spiny Dogfish failed to develop at this time because of the low potency of the livers of Spiny Dogfish of the Atlantic coast. The livers of Atlantic coast Spiny Dogfish contained only 2,000–3,000 units of vitamin A, while Spiny Dogfish from the Pacific coast contained an average of 15,000 units (Tressler and Lemon, 1960). In these fisheries the livers were removed from the sharks and the carcasses were discarded in the ocean, although in some cases small quantities of dried fins and shark leather were also produced.

The west coast fisheries expanded dramatically, with peak landings in 1941–43. By the late 1940's, these fisheries were depleted because of overfishing and fishing in the nursery areas. Finally, the appearance of synthetic vitamin A on the market in 1950 caused the fishery to be discontinued (Springer, 1952). The Soupfin Shark fishery of the west coast fishery has never recovered; a publication on the marine resources of California (Leet et al., 1992) describes five current shark fisheries but does not even mention the Soupfin Shark

The commercial shark fishing of the 1940's gave impetus to the preparation of the greatest work on sharks of the twentieth century. In 1945, the U.S. Fish and Wildlife Service republished a small booklet created by the Anglo-American Caribbean Commission titled "Guide to Commercial Shark Fishing in the Caribbean Area." Its foreword stated "Shark fishing is becoming increasingly more important throughout the Western Hemisphere because the valuable yield of vitamin oils, high quality leather, and food products obtained from sharks." The biological section of the work was done by Henry B. Bigelow and William C. Schroeder of the Museum of Comparative Zoology at Harvard University. Bigelow and Schroeder (1948) would expand this work into the first volume on sharks, of the monumental series "Fishes of the Western North Atlantic." This work, reprinted in 1975, remained as the reference work on North American sharks for the rest of the century. The taxonomy of North American sharks was in a state of confusion at the time, and this volume did much to clear up many problems. The work set such a high standard for the series that subsequent volumes would appear slowly over the next few decades.

The U.S. Navy Era: the Shark Chaser

In the 1930's, many people questioned whether sharks would attack men. Barely two decades before, there had been well publicized shark attacks on humans off New Jersey in 1916, but these had become questionable as there were many unanswered questions. There had been other publicized attacks on bathers in the late 1800's but those had been forgotten. And in 1937, the well-known ichthyologist, E. W. Gudger, of the American Museum of Natural History, wrote an article titled "Will Sharks Attack Human Beings?", where he stated that many people, including the noted Dr. William Beebe, doubted that sharks would attack humans. Although Gudger cited two clear cases of shark attacks and concluded his article with the statement "*Sharks Sometimes Do Attack Human Beings*" [his italics], he expressed his and others beliefs that the barracuda (Sphyraenidae) was responsible for most alleged cases of shark attack.

The naval engagements of World War I were fought mainly in the cold waters of the North Atlantic. Other naval battles taking place in other oceans, and resulting in high casualties, e.g., the battles of Coronel and Falklands in 1914, also occurred in cold waters and, in most sinkings, there were few or no survivors in those frigid waters. Life expectancy of a sailor in the cold water was so brief, that most perished of hypothermia before they could be rescued.

The major naval battles of World War II occurred mainly in the North Atlantic and in the tropical Pacific. In the North Atlantic, it was primarily the battle of the U-boats against the Allied convoys, with relatively few engagements of surface forces in oceanic waters. The survivors of ships torpedoed and sunk at high latitudes had poor chances of reaching a life boat and no chance at all if not pulled from the water in a short time, while the U-boat sailors seldom had a chance to escape their damaged "underwater coffins." By contrast, the naval war in the Pacific Ocean and many U-boat attacks in the Caribbean Sea and the South Atlantic Ocean occurred in warm tropical waters, where sailors could survive floating for many hours or even days while hoping for rescue. Rescued sailors and aviators often told of shipmates being attacked and consumed by sharks. Early in this war, military personnel knew that sharks were a definite problem for those who ended a battle floating in the ocean.

In February 1941, anthropologist Henry Field[10], of the Field Museum of Natural History in Chicago, was asked to serve as "Anthropologist to President Roosevelt," advising the President on the many refugee problems caused by the war in Europe, and as a member of the Special Intelligence Unit at the White House. In 1942 Field was asked to fly to Trinidad to investigate complaints regarding U.S. enlisted men there. After accomplishing

[10]Henry Field (1902–1986). An American anthropologist, was born in Chicago and educated at Sunningdale, Eton, and Oxford (B.A., 1925; M.A., 1930; D.Sc., 1937). He had a keen interest in life-saving equipment, and he invented many life saving devices including the shark deterrent and a signal mirror for downed airmen.

his mission, Field reminisced about his talks with torpedoed merchant seamen who had escaped from sharks. In his 1953 autobiography, Field wrote: "Night after night I thought of these men in the water, holding onto rafts or upturned lifeboats or lying in rubber boats, with sharks cutting through the water around them. I wrote the President a memorandum suggesting that we try to develop a shark repellent" (Field, 1953:329). Field was instructed to discuss the matter with the chief of the Bureau of Aeronautics of the U.S. Navy. Knowing little about sharks, Field called upon his friend, Harvard zoologist, Harold J. Coolidge[11] then with the Office of Strategic Services, and the two discussed the problem. The two men then called on Admiral Ralph Davidson, Chief of the Bureau of Aeronautics, who became interested in the idea, mainly from the psychological point of view.

The main problem was convincing the U.S. Navy that sharks were a problem for those finding themselves floating in the ocean after a battle. At the time, some senior naval personnel believed that "since authentic incidents of sharks bites were extremely rare, it was a mistake to recognize the danger by supplying a deterrent" (Burden, 1945:344). One naval officer wrote, "We have no record of anyone who had taken an oath to the U.S. Navy ever having been bitten by a shark" (Field, 1953:330). Nevertheless, it was agreed to proceed with the research since the elimination of anxiety was an important factor in survival.

In early June 1942, the Navy Bureau of Aeronautics was tasked with developing a substance to protect swimmers from attacks by sharks and other "predatory fishes," as barracudas were thought to attack swimmers also. On 26 June 1942, the Bureau of Aeronautics, joined by the Merchant Marine and the Army Air Force, requested the National Research Council initiate a project to find a shark deterrent to protect men adrift in life preservers (Burden, 1945). A team was soon assembled under William Douglas Burden, trustee of the American Museum of Natural History and founder and president of Marine Studios, as responsible investigator. Included were Stewart Springer, shark fisherman and senior investigator; Arthur McBride, from Marine Studios as junior investigator; C. M. Breeder, from the New York Aquarium, consulting investigator; David Todd, chemist at Harvard; "Dr. French," consulting chemist; and A. P. Black, a chemist at the University of Florida (Field, 1953; Gilbert, 1963). The Navy assigned J. M. Fogelberg and C. R. Wallace to the team. Tests were conducted from April 1943 to July 1944.

The initial experiments were carried out at Woods Hole Oceanographic Institution on Smooth Dogfish, and described by Springer (1955). According to Burden (1945:344) the tests carried out "were discouraging. The strongest fish poisons, even in high concentrations, failed. The poison killed the sharks in about 1/2 h, but in the meantime they ate all the bait. Supersonics, stenches, irritants, and different types of ink clouds failed."

Subsequent testing was carried out at La Jolla, Calif., the Gulf of Guayaquil, Biloxi, Miss., and St. Augustine, Fla. Of the experiments, Springer (1943:23) wrote: "At some point here we lost the control afforded by the chemical work by biological assay" and the experiments became "tests," because the difficulty in eliminating variables and lack of rigid controls.

Eventually the investigation focused on shark fishermen's lore provided by Springer. It was said that when a longline fishing for shark was lost, the area was ruined to shark fishing for several weeks because sharks did not like the smell of dead sharks. A substance released by the decomposing sharks prevented other sharks from feeding. After many tests, the investigators settled on copper acetate, the copper ion being recognized as the substance that inhibited fish from feeding. They added a nigrosine dye to mask the scent of the swimmer and to diffuse around him a dark cloud to screen him from view. After tests conducted off St. Augustine in May 1944, the investigators settled on a simple composition for the deterrent: 80% nigrosine black dye, 20% copper acetate, held together by a waxy binder of such solubility to cause the 6-ounce cake to dissolve in seawater over a period of 3–4 hours (Burden, 1945). The urgency of the times permitted only limited testing of the repellent, which was named "Shark Chaser," but it soon became a standard issue of survival gear for the services.

Because the shark hazard was perceived as more of a morale or perception problem than a real problem, the Navy tried other solutions while the shark repellent was being developed. Naval aviators were particularly prone to ending a battle wet and floating in the ocean due to battle damage to their aircraft, a faulty engine, or running out of fuel. The stalwart naval aviators thought nothing of confronting a well-trained, armed enemy in the sky or of landing on a pitching and heaving carrier deck, but the idea of having to deal with sharks when forced to leave their aircraft was a different matter.

These fears prompted the U.S. Navy in 1944 to issue a nonsense-filled pamphlet titled "Shark Sense," (Fig. 13, 14) designed to allay the fears of naval aviators concerning sharks. It concluded with the editorial comment of "The natural conclusion is that the shark offers no unusual hazards to a swimming or drifting man; in fact the chances that a man will be attacked by a shark or a barracuda are infinitesimal." (U.S. Navy, 1944:23).

It is doubtful that anyone took "Shark Sense" too seriously, and by the end of the war, numerous inci-

[11]Harold Jefferson Coolidge, Jr. (1904–1985) was an American zoologist and one of the founders of the International Union for the Conservation of Nature (IUCN), and served as its President from 1966 to 1972 and as Honorary President after that. He was also a founding director of the World Wildlife Fund (WWF). He received a B.S. from Harvard in 1927, and the he worked as curator at the Museum of Comparative Zoology at Harvard. He was a primatologist by training, and he published a revision of the genus *Gorilla* and the first account of bonobos, *Pan paniscus*. During World War II he worked for the Office of Strategic Services (OSS). He received the Legion of Merit in 1945 and the J. Paul Getty Wildlife Conservation Prize in 1980.

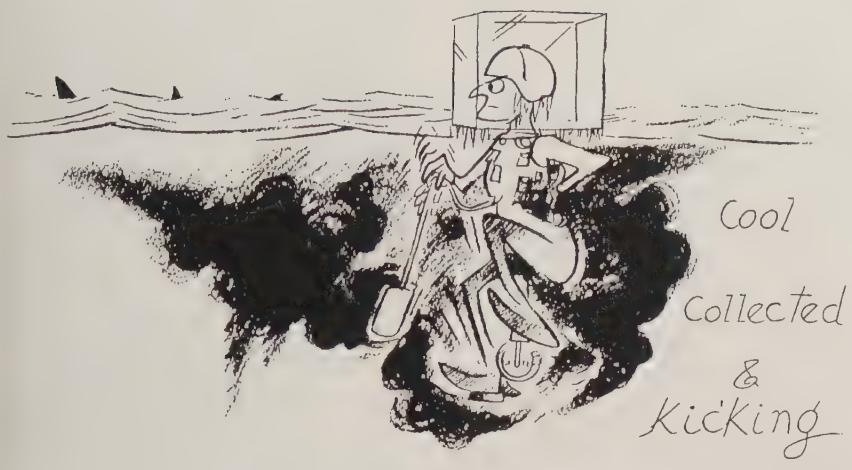

Figure 13.—Illustration of a downed airman using the "Shark Chaser" (U.S. Navy, 1944).

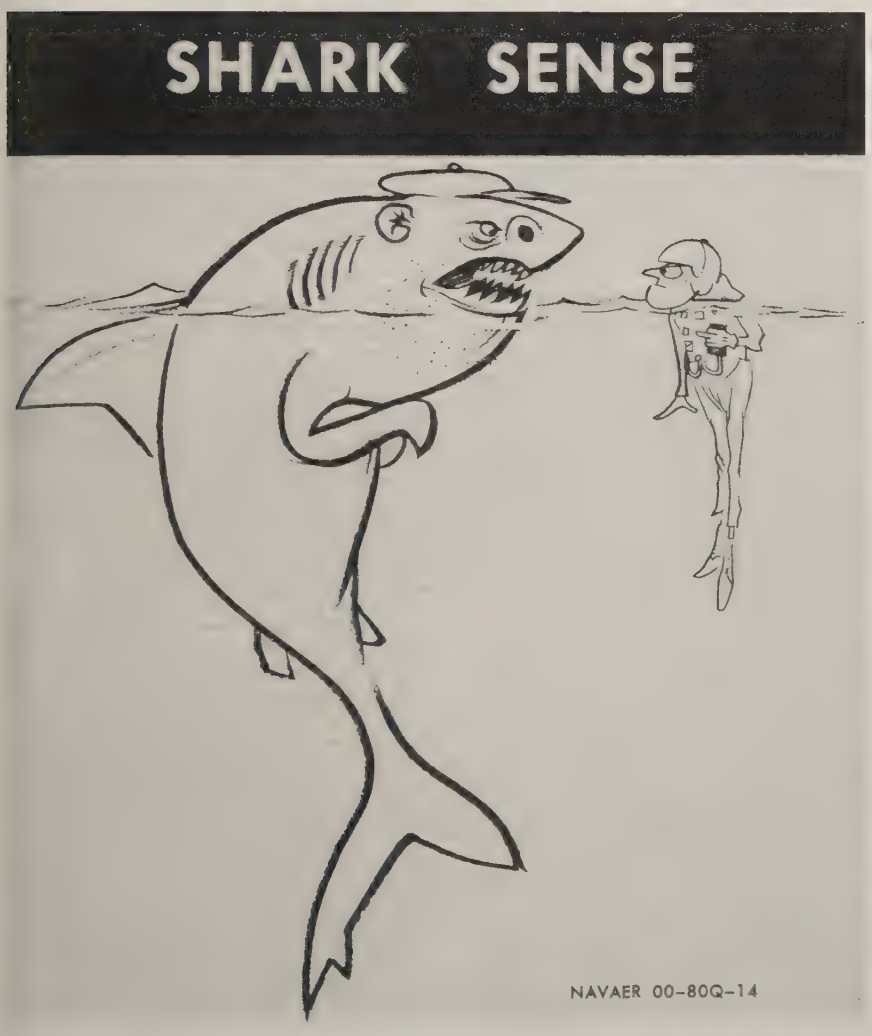

Figure 14.—Cover of "Shark Sense" (U.S. Navy, 1944).

dents demonstrated that sharks would attack floating sailors or downed aviators. Perhaps the most famous of these incidents was the sinking of the cruiser USS *Indianapolis*. The ship carried 1,196 men on board when it was torpedoed on the night of 30 July 1945. Some 400 men went down with the ship. Of the 800 men that went into the water, only 316 survived after four days of drifting in the tropical water. Many were taken by sharks. The Action Reports (see below) of the rescuers left no doubt that sharks had been responsible for many of the deaths. One of the rescuers, the Captain of the USS *Helm* wrote: "About half of the bodies were shark-bitten, some to such degree that they more nearly resembled skeletons. From one to four sharks were in the immediate area of the ship at all times. At one time, two sharks were attacking a body no more than fifty yards from the ship, and continued to do so until driven off by rifle fire" (Lech, 1982:157–58). Subsequent editions of "Shark Sense" no longer said that the chances of shipwrecked sailors and downed airmen being attacked by sharks were "infinitesimal."

The 1959 version of "Shark Sense" extols the virtues of the "Shark Chaser," and its nigrosine dye cake that downed aviators were supposed to release into the water, with the assumption that it would repel sharks and hide the aviator from the shark's sight (U.S. Navy, 1959). It closed with: "Your best protection is your Shark Chaser. Sharks take one look at the magnificent black aura surrounding a downed pilot and recall urgent business elsewhere."

In the decades following World War II, there were numerous reports concerning the ineffectiveness of "Shark Chaser." In a report titled "Airmen Against the Sea," Llano (1955) analyzed a sample of 607 accounts of survival experiences after ditching at sea from 1940 to 1955. Llano (1955:72) wrote that "Unfortunately the narratives provide no evidence of "Shark Chaser" used under survival conditions with sharks present. Skin divers

[of the British Shallow Water Diving Unit] who have used it put little faith on it... Beyond question the greatest value of the "Shark Chaser" was the mental relief and sense of security it afforded the men who had it on hand." Nevertheless, "Shark Chaser" remained in the military supply system until 1976, when it was discontinued, based on recommendations from the Office of Naval Research. In his excellent review of the shark repellent problem, Baldridge (1990), referred to "Shark Chaser" as "a useful psychological crutch for the times." That is all it was, but its creation marked the beginning of research into the sensory biology and behavior of sharks.

The Office of Naval Research Era

I have decided to call this period the Office of Naval Research Era, as being different from the previous U.S. Navy era when the sole interest was on developing a shark deterrent. In terms of the knowledge of sharks and shark research, this was the first time biologists studied the biology and the sensory mechanisms of sharks and tried to understand their behavior. Previously, ichthyologists were satisfied with being able to distinguish and name species of sharks, and sharks were only mentioned briefly in faunistic works with but few facts about them

The Office of Naval Research (ONR) was created within the Department of the Navy in 1946 for the purpose of encouraging and fostering research related to naval interests and national security. Starting in the late 1950's the ONR embarked in a research and data collection programs to learn about sharks, their behavior, and shark attacks on humans. These programs were created, developed, and managed by one man, Sidney R. Galler, who headed the Biology Branch of ONR. According to Captain H. David Baldridge[12], USN, "If you had a good idea for research on sharks, you went to Sid and almost surely would get funding, for he saw practical justification (i.e., a Navy need) in almost every phase of basic research."

In 1958 ONR established the Shark Research Panel of the American Institute of Biological Sciences (AIBS). Through this panel and other direct means, ONR generously funded research and conferences to develop means of protecting naval personnel from shark attack. One of the first accomplishments of the Shark Research Panel was to establish, with ONR funds, the worldwide data collection system known as the "Shark Attack File" at the Smithsonian Institution. Under the direction of Perry Gilbert, data was collected from newspapers around the world, and from direct sources whenever possible, on some 1,500 shark attacks over nine years. The data was summarized in 1974 by David Baldridge in "Shark attack: a program of data reduction and analysis," which contains most of what we know today about shark attacks.

From the late 1950's to the 1980's, ONR funding was responsible for much of what was learned about the sensory biology of sharks. Many shark researchers (Eugenie Clark, Perry Gilbert, Samuel Gruber, A. J. Kalmijn, and H. D. Baldridge, among others) were funded by ONR to carry out research to elucidate the sensory biology of sharks. This work resulted in some excellent books that summarized the available knowledge of shark sensory biology and behavior. The first of these volumes was "Sharks and Survival," edited by P. W. Gilbert (1963) "with the cooperation of the members of the Shark Research Panel of the American Institute of Biological Sciences." This volume was followed by "Sharks, Skates, and Rays," edited by P. W. Gilbert, R. F. Mathewson, and D. P. Rall (1967), and by "Sensory Biology of Sharks, Skates, and Rays," edited by E. S. Hodgson and R. F. Mathewson (1978). The last of these useful works was "Shark Repellents from the Sea," edited by B. J. Zahuranec (1983), who had led ONR's shark research for many years.

After the early 1970's, the perception of the danger that sharks posed to downed aviators had come full circle and it was again considered negligible. Several factors contributed to that perception. The greater reliability and ruggedness of jet engines reduced the number of aviators having to ditch their aircraft due to engine failure or battle damage. The development of electronic personnel or aircraft locator devices (such as Emergency Locator Transmitters, Crash Position Indicators, etc.) during the Vietnam War reduced the possibility of personnel spending long times floating in the ocean.

Baldridge (1969) had demonstrated the impracticability of deterring shark attacks by waterborne chemicals, so the idea of shark repellents had lost some of its appeal. However, through the mid 1980's, ONR continued to fund the search for shark repellents. Much money and research effort was spent on pardaxin, a secretion of the Moses Sole, *Pardachirus marmoratus*, which has shark repelling properties (Clark and George, 1979), but no practical applications were found. All these factors contributed to ONR losing interest in funding research on shark repellents.

ONR's interest in sharks was not limited to their sensory abilities and shark repellents. According to a 1982 article by Gerald D. Sturges, in the *Orlando Sentinel*, the Navy founded a project "to convert the shark into a remote-controlled torpedo that could ram a ship while carrying a load of explosives" (Sturges, 1982; Fig. 15). The research was conducted under the name of Project Headgear at Mote Marine Laboratory (Sarasota, Fla.) and the Lerner Marine Laboratory (Bahamas) from 1958 to 1971. Sturges (1982) wrote that the program "ended unsuccessfully after 13 years of testing. However, the Navy continues to classify it as secret and refuses to release anything. The Office of Naval Research said only that 'the report is classified secret and is currently being reviewed for declassification.'" My attempt to obtain information about the project from ONR in 2013 also yield-

[12]Baldridge, Capt. H. D., USN. Letter to author, 21 April 2013.

Figure 15.—Project Headgear (Sturges, 1982).

ed nothing, and I could not determine whether the project was declassified or not.

The "Jaws" Era

In 1974, Peter Benchley's great novel "Jaws" was published, followed a year later by the movie of the same title. The movie became one of the most influential movies in history, affecting the attitudes of millions of people towards sharks and the ocean. The movie's powerful images were remembered every time the movie-watchers entered a beach in the following decades. The movie also set off a shark killing frenzy that lasted decades.

Shortly after the movie appeared, shark fishing as sport became popular, and in the next decade hundreds of shark fishing clubs and tournaments appeared along the U.S. east coast. These tournaments were held monthly at many seaside locations during the summer months. The movie caused such antipathy towards sharks that tournaments had prize categories for "the most sharks killed" and the "greatest number of pounds of shark landed." Emulating the fisherman in "Jaws," shark fishermen saw themselves as heroes ridding the seas of sharks. This unfortunate attitude and ecological catastrophe lasted for nearly two decades. The U.S. recreational shark landings for 1979 were 11,512 t; by 1989 they had decreased to 1,666 t (NOAA, 1992), and to 660 t by 2002 (NOAA, 2003).

The Shark Fin Fishery Era

In 1972, after some 25 years of open antagonism and hostility between the United States and The People's Republic of China, and after extensive diplomatic negotiations, President Richard Nixon visited China, as a step in the normalization of relations between the two countries. During the next two decades, complex economic and financial ties developed steadily between the two countries. In due time, the combination of Chinese energy and cheap labor, American capital and know-how, and other factors helped make China the manufacturing colossus of the early twenty-first century.

China's economic boom, beginning in the late twentieth century, resulted in an improved standard of living for some segments of the Chinese population, and a greater proportion of society was able to afford luxuries that had previously been out of reach. One of these luxuries is shark fin soup. In China, a soup utilizing the fibers found in shark fins has been considered a symbol of prosperity and health for centuries. It is a dish served at special occasions such as weddings, and a demonstration of wealth and class. Consequently, the demand of shark fin soup increased substantially.

Soon after the establishment of diplomatic relations between the United States and China in January 1979, American and Chinese merchants were figuring out what business could be conducted with the other. When Chinese merchants expressed the growing demand for shark fins, American entrepreneurs sought to fulfill it. The demand became high in China and other Asian countries, and sharks were one of the few fish resources not targeted or fully utilized by U.S. commercial fisheries. While there was a strong U.S. recreational fishery for sharks, the commercial fisheries had not targeted sharks since the late 1940's. With the exceptions of Porbeagle, *Lamna nasus*, that had been targeted in the early 1960's off New England (Campana et al., 2001), and Dusky Sharks, *Carcharhinus obscurus*, that had been taken incidentally in Japanese tuna fisheries in the Gulf of Mexico in the same decade, the shark stocks in the southeastern U.S. waters were relatively high (Castro, 2011).

It took about a decade for business and financial channels to develop, and by the late 1970's substantial changes had occurred in shark utilization. The high prices paid for the fins encouraged entry into the shark fishery. The tuna and swordfish fisheries that previously had discarded sharks (dead or alive) now began to keep sharks for their fins. The low price paid for the meat, resulted in fishermen just removing the fins from sharks and discarding the shark into the ocean, thus saving their freezer space for the more lucrative tunas and swordfish. This wasteful practice became known as "finning."

In just one decade, the U.S. commercial shark landings grew from 135t in 1979 to 7,172 t in 1989 (NOAA, 1992). Conservation organizations and regulatory agencies were both concerned about the rapid growth of the unregulated shark fishery. On 3 June 1989, the five east coat fishery management councils requested that the Secretary of Commerce develop a fishery management plan for the shark fishery. Their concern was that it would take too long for the five councils to develop their own, and that, in view of the rapidly growing fishery, the delay could cause irreparable damage to the shark stocks.

A team of NOAA personnel was assembled in 1989 to prepare a management plan for sharks of the east coast. The National Marine Fisheries Service had little data on shark catches, and what existed was not broken down by species. So personnel set out to try to obtain data on shark landings from the

commercial industry. Little data were available because, in general, fishermen did not record the information needed for stock assessment purposes (e.g., landings by species, catch per unit effort, etc.) or for the regulation of the fishery. Nevertheless, a shark fishery management plan was prepared (NOAA, 1992), and published 10 December 1992. The plan was data-deficient for the reasons cited, and some of its predictions would prove wrong. But the key to its success was a provision for change and improvement by designating an "Operational Team" which could amend the plan as new data were obtained. Over the next two decades the plan was amended many times. The plan not only protected the shark stocks but it ushered a new era of research on sharks. The plan and its effects will be covered in a future article.

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Comparing Autonomous Underwater Vehicle (AUV) and Vessel-based Tracking Performance for Locating Acoustically Tagged Fish

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ABSTRACT—Autonomous underwater vehicles (AUV's) are increasingly used to collect physical, chemical, and biological information in the marine environment. Recent efforts include merging AUV technology with acoustic telemetry to provide information on the distribution and movements of marine fish. We compared surface vessel and AUV tracking capabilities under rigorous conditions in coastal waters near Juneau, Alaska. Tracking surveys were conducted with a REMUS 100 AUV equipped with an integrated acoustic receiver and hydrophone. The AUV was programmed to navigate along predetermined routes to detect both reference transmitters at 20–500 m depths and tagged fish and crabs in situ. *Comparable boat surveys were also conducted. Transmitter depth had a major impact on tracking performance. The AUV was equally effective or better than the boat at detecting reference transmitters in shallow water, and significantly better for transmitters at deeper depths. Similar results were observed for tagged animals. Red king crab,* Paralithodes camtschaticus, *at moderate depths were recorded by both tracking methods, while only the AUV detected Sablefish,* Anoplopoma fimbria, *at depths exceeding 500 m. Strong currents and deep depths caused problems with AUV navigation, position estimation, and operational performance, but reflect problems encountered by other AUV applications that will likely diminish with future advances, enhanced methods, and increased use.*

Introduction

Detailed information on the movements and distribution of marine species is necessary for stock assessments and, when combined with habitat information, for the implementation of ecosystem-based management (Cadrin and Secor, 2009; Goethel et al., 2011). Establishing baseline data is also becoming increasingly important for assessing changes in population and community structure in relation to environmental shifts in ocean conditions (Perry et al., 2005; Rose, 2005; Doney et al., 2012; Aschan et al., 2013).

Emerging technologies, including acoustic telemetry and remote monitoring with autonomous underwater vehicles (AUV's), can enhance efforts to address research and management issues. Acoustic telemetry, defined here as the detection of fish and other aquatic macrofauna tagged with acoustic transmitters and located using submerged hydrophones (Winter, 1996; Arnold and Dewar, 2001), can provide detailed information on the distribution, movements, and habitat use of marine species.

This approach has many advantages over conventional tagging (i.e., identifying individuals or groups of fish based on external marks or tags) and recovery methods, which provide information based solely on where the tagged individuals were recaptured and can be biased by disproportional recovery efforts, vulnerability to capture, and variable reporting rates (Seber, 1982; Buckland, 1980). Individuals tagged with acoustic transmitters can be repeatedly located without having to be captured. This factor can be a major advantage particularly when working in isolated areas or studying species that are sensitive to handling, difficult to catch, or associated with substantial bycatch.

Despite these advantages, the utility of acoustic telemetry can be offset by the limited reception range (typically hundreds of meters) and the tradeoffs between transmitter size, transmitting power and operational life (Arnold and Dewar, 2001; Pincock and Johnston, 2012), and the vast distances, depths, limited access, and adverse conditions (e.g., rough seas, stratification) often encountered in marine waters. To counter these limitations, a variety of methods have been used to actively locate acoustically tagged fish from vessels (Holland et al., 1985; Marsac and Cayre, 1998; Pepperell and Davis, 1999; Brill et al., 2002; Meyer and Holland, 2005; Ng et al., 2007; Taggart et al., 2008).

However, high operational costs and limited vessel availability can significantly reduce vessel-based efforts, especially when working in remote areas. Inclement weather can further impact the amount of time that tracking is feasible, particularly for smaller vessels, and substantially reduce acoustic signal reception (Goodman, 1990; Winter, 1996; Ross and Lueck, 2003). Tracking from larger vessels can be logistically challenging, electronically noisy, and often conflicts with other scheduled tasks or research activities.

Alternatively, stationary receiver/hydrophone arrays have been used to

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cordon off marine areas and detect tagged individuals moving within reception range (Voegeli et al., 2001; Simpfendorfer et al., 2002; Welch et al., 2003; Grothues and Able, 2007; Bishop et al., 2010). Stationary tracking is less affected by adverse conditions, and allows for the collection of extended time series data of migratory species or fine-scale positioning studies in localized areas. However, this approach is also equipment intensive, often dependent on the local geomorphology, and may be logistically challenging or prohibitively expensive compared to mobile tracking methods.

Both gliders and propelled AUV's can mitigate some of the challenges associated with existing tracking methods by expanding vessel-based capabilities and providing a flexible supplement to stationary arrays, as they have for other applications including military, industrial, and scientific research (Wernli, 2000; Hagen et al., 2003). AUV's are increasingly being used to document physical, chemical, and biological characteristics of the marine environment (Hibbert, 1997; Moline et al., 2005; Jones et al., 2008) and have tremendous potential to provide information on the biology and status of fish populations (Clarke et al., 2010).

Recent efforts have produced AUV's with acoustic telemetry capabilities. At least one AUV equipped with an integrated acoustic receiver and hydrophone is now used routinely as a telemetry platform to locate tagged fish in estuarine and shallow coastal settings in the eastern United States (Grothues et al., 2009, 2010, 2012). In addition to the enhanced tracking capabilities provided by the vehicle, the AUV's high frequency side-scan sonar and environmental sensors make it possible to integrate telemetry data (e.g., fish presence and location) with bathymetric and environmental information. However, until now AUV performance has not been rigorously tested in comparison to vessel-based (i.e., surface) tracking, and never in deep waters where AUV's have demonstrated capabilities for other applications.

We evaluated the performance of an AUV for collecting acoustic telemetry data and associated hydrographic information in coastal waters of southeastern Alaska during May–June 2010. The primary goal of the study— determining the feasibility of using AUV's to track marine animals—focused on both the operational capabilities of the AUV and the performance of the telemetry component of the system. Here we discuss the second of these two issues, with generalized references to the first.

The specific objectives of this portion of the study were to 1) determine the range and fidelity of the AUV-based acoustic receiver/hydrophone system for recording ultrasonic reference transmitters (similar to those used for biotelemetry studies) placed at known locations and depths in a complex marine environment, and 2) compare telemetry data obtained for reference transmitters and free-ranging acoustically-tagged animals using both AUV and vessel-based tracking to determine if AUV platforms provide comparable or better information than conventional methods.

Methods

Study Area

The study area, located near Juneau, Alaska (Fig. 1), was chosen because of its demanding conditions and proximity to NOAA's National Marine Fisheries Service (NMFS) support facilities in Auke Bay. The geomorphology of the area is complex with many ocean channels, bays, inlets, and islands. Water depths range from shallow nearshore habitats to depths exceeding 500 m. Extreme tidal fluctuations, freshwater intrusion from local rivers, and strong, highly variable currents further complicate AUV operations. Survey sites within the area were sampled with a CTD (Model 19plus, Sea-Bird Electronics[1], Bellevue, Wash.) from 11 May to 18 June 2010 in conjunction with AUV and boat tracking missions. Sampling depth (from surface to ocean floor) ranged from 74 to 92 m at Portland Island and from 511 to 587 m at Point Retreat.

[1]Reference to trade names or commercial firms does not imply endorsement by the National Marine Fisheries Service, NOAA, or Rutgers University.

Transmitters

Twelve moorings instrumented with acoustic reference transmitters were deployed within the study area during April 2010. One array of six moorings was located in shallow water (100–112 m) west of Portland Island in northern Stephens Passage, while a second array was deployed in deep water (574–585 m) southwest of Point Retreat in southern Lynn Canal (Fig. 1). The moorings of both arrays were spaced 200 m apart and positioned to form a 2 mooring x 3 mooring grid to maximize the data collected during the tracking surveys. Acoustic transmitters (Model MA-TP16-33, Lotek Wireless, Newmarket, Ontario, Can.), rated to a depth of 700 m, were attached to the mooring line to provide acoustic signals at known locations and depths. The transmitters (6.2 cm in length, 1.6 cm in diameter, and weighing 27 g) emitted a 76.8 kHz, code division multiple access (CDMA) signal burst every 2 s with power output of 155 dB (referenced to 1 μPa at 1 m).

The transmitters were also equipped with a temperature sensor accurate to ± 0.8°C and depth sensor rated to 700 m depths and accurate to ± 10.5 m. Sensor data were transmitted as part of the signal burst, and alternated every 2 s between depth and temperature. The transmitters were randomly selected and attached to the mooring at approximate depths of 20 and 100 m at the Portland Island site, and 20, 100, 200, and 500 m at the Point Retreat site. Transmitters were oriented perpendicular to the line (i.e., horizontal, as they would be if implanted in fish) and attached with electrical tape. The battery end of the transmitter was used as the attachment point so that the transducer was unobstructed.

Sablefish, *Anoplopoma fimbria*, and red king crab, *Paralithodes camtschaticus*, were captured and tagged with

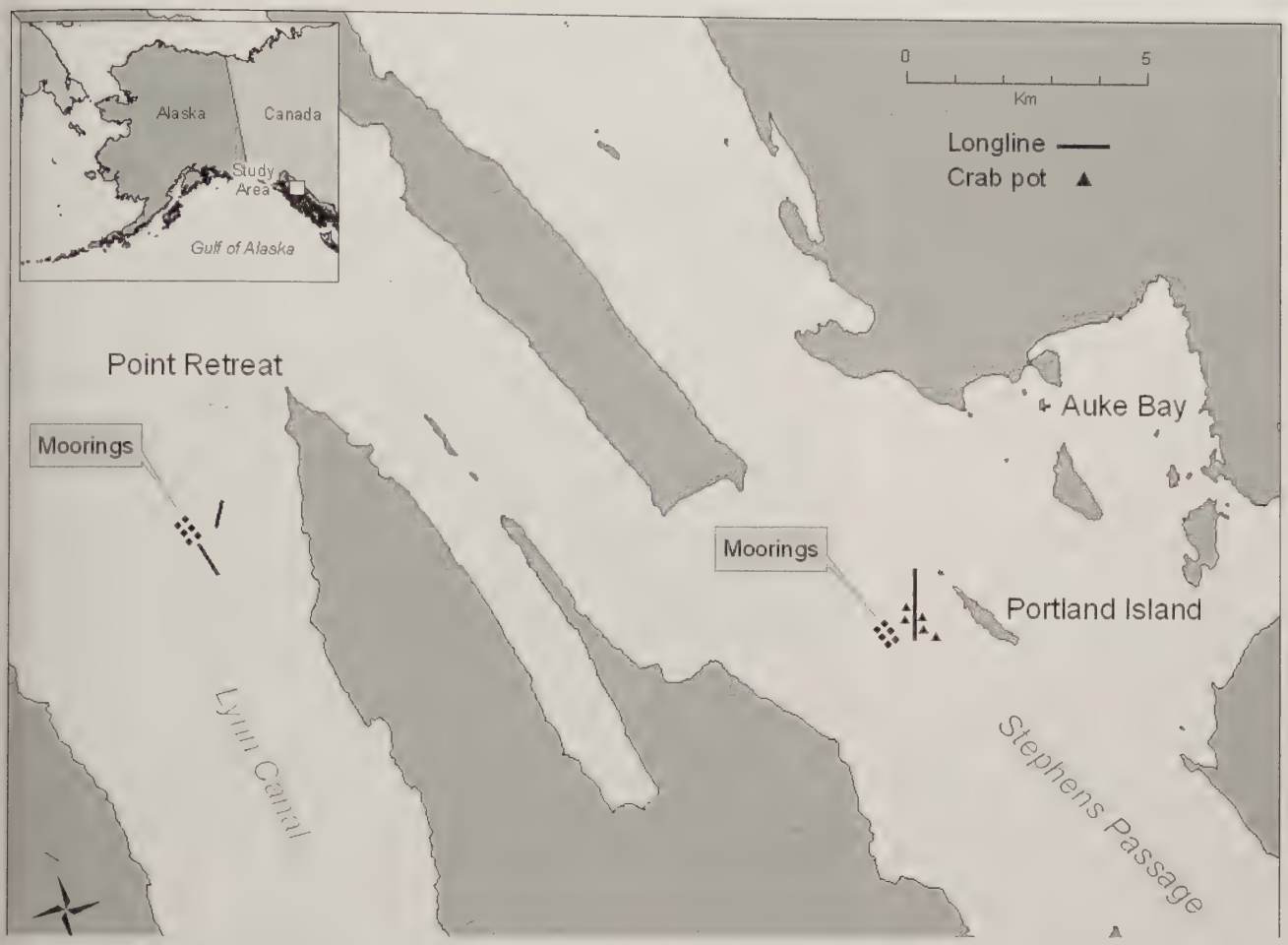

Figure 1.—The study area near Juneau, Alaska, showing the position of research moorings instrumented with acoustic transmitters. The location and type of fishing gear used to capture fish and crabs for tagging are also indicated. AUV and vessel-based tracking surveys were conducted in the vicinity of the moorings. Missions were also conducted in Auke Bay to calibrate equipment and refine tracking methods.

acoustic transmitters to supplement the reference transmitters and to provide acoustic targets with more realistic reception patterns. The crabs were captured with pyramidal crab pots (described by Browning, 1980) deployed and fished overnight near Portland Island at depths of 110–130 m (Fig. 1). Sablefish were captured with commercial longline gear (described by Skud and Hamley, 1978; Browning, 1980). The longline gear was retrieved 2–3 h after being deployed to minimize capture-related injuries and stress.

Selected individuals were tagged with acoustic transmitters (Model MM-M16-33, 6.4 cm x 1.6 cm, 29 g Lotek Wireless). These transmitters had the same signal characteristics as the reference transmitters, but were not equipped with temperature and depth sensors. Sablefish were tagged by surgically implanting transmitters in the abdominal cavity.[2] Transmitters were attached externally to the dorsal carapace of the crabs using overlapping strips of Kevlar and fiberglass tape, saturated with quick-drying epoxy (Adtech EA-604 resin and hardener, Cass Polymers, Madison Heights, Mich.). Tagged crabs were held and observed for 1–2 h before release.

[2]Eiler, J. H., T. M. Grothues, J. A. Dobarro, M. M. Masuda, D. W. Carlile, J. K. Nielsen, N. Hillgruber, and J. J. Vollenweider. 2011. Use of an autonomous underwater vehicle (AUV) for tracking acoustically-tagged fish in complex marine environments in coastal Alaska. NPRB Proj. 928 Final Rep. N. Pac. Res. Board, Anchorage, Alaska, 90 p.

Survey Operations

Survey missions employed a REMUS 100 AUV (Hydroid, Inc., Pocasset, Maine, a subsidiary of Kongsberg Maritime, Kongsberg, Norway). This torpedo-shaped vehicle (160 cm in length, 19 cm in diameter, 31 kg) had a maximum operating depth of 100 m (although typically limited to 80–85 m as a safeguard), cruising speed over ground of 0.25 to 2.57 m/s, and

functional temperature range of 0° to 38°C (Hydroid, 2007; Fig. 2). Operational parameters and mission instructions were programmed, simulated, and uploaded to the AUV prior to launch.

AUV navigation applied dead reckoning using data from the internal compass, yaw-rate sensor, propeller revolution rate, and sea bed reflections (bottom track) of the downward looking 1200 kHz Acoustic Doppler Current Profiler/Doppler Velocity Log (ADCP/DVL, Teledyne RD Instruments, Poway, Calif.) to provide an estimate of speed-over-ground velocity and heading when within 30 m of the seafloor (Hydroid, 2007).

Course corrections were made by periodically surfacing to obtain position fixes using the vehicle's global positioning system (GPS) receiver. The AUV was either programmed to surface at designated locations or placed in "navigate" mode, which used complex software logic to determine when additional GPS fixes were needed based on an interpretation of the sensor data. An acoustic modem provided intermittent communication with the support vessel. An acoustic transmitter (same specifications as the reference transmitters) was also attached to the dorsal side of the vehicle and monitored by the same acoustic tracking gear installed on the support vessel for tracking tagged fish (see below); this approach provided independent and more frequent data on AUV position and depth than the modem, albeit at a reduced range. A radio transmitter attached to the AUV and RF receiver and directional antennas installed on the vessel were used to determine when the AUV surfaced and to relocate the vehicle for recovery.

In addition to the operational sensors, the AUV was instrumented with a 600 kHz side-scan sonar (Marine Sonic Technology, Ltd., White Marsh, Va.), and sensors for measuring environmental conditions, including water conductivity and temperature (YSI, Inc. Yellow Springs, Ohio), pressure for estimating depth (Honeywell, Columbus, Ohio), dissolved oxygen (Aandreaa Data Instruments, Inc., Bergen, Norway), and two triplet optical sensors (Wet Labs, Philomath, Oreg.). One optical sensor measured chlorophyll *a*, colored dissolved organic matter (CDOM), and backscatter at 880 nm, while the second measured backscatter at 470 nm, 532 nm, and 660 nm. The vehicle was also equipped with an integrated acoustic receiver/hydrophone (Model WHS 3050, Lotek Wireless) capable of detecting, identifying, and recording CDMA transmitter signals. The receiver was mounted to the forward bulkhead of the AUV with the hydrophone oriented horizontally (Fig. 2).

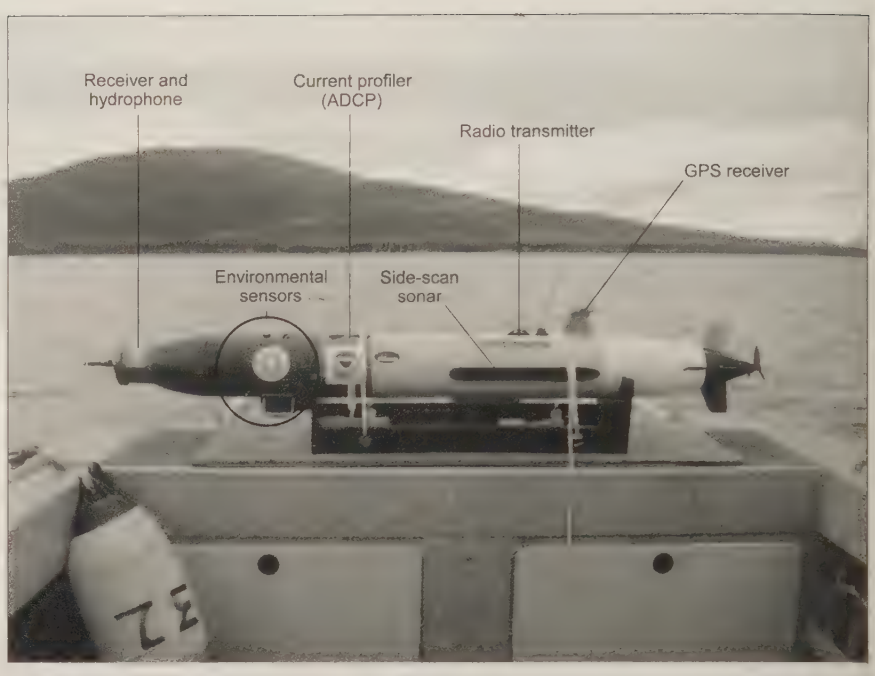

Figure 2.—REMUS 100 autonomous underwater vehicle (AUV) used to conduct tracking surveys in marine waters near Juneau, Alaska, during 2010. The AUV was equipped with a receiver and hydrophone for detecting and recording acoustic transmitters, environmental sensors, Acoustic Doppler Current Profiler/Doppler Velocity Log (ADCP/DVL), side-scan sonar, radio transmitter for locating the vehicle on the surface, and GPS receiver for collecting positioning data. The AUV was either launched from shore or transported to survey sites on a support vessel (shown above).

An 8 m aluminum boat was used to deploy and recover the AUV, and conduct vessel-based tracking surveys. The boat was instrumented with an acoustic receiver (Model MAP_600 RT, Lotek Wireless) and stereo hydrophones (Model LHP, Lotek Wireless) capable of detecting, identifying, and recording CDMA transmitter signals. The hydrophones were attached to vertical aluminum poles on the port and starboard (spaced 2 m apart) and submerged to 1 m depth. Tracking speed over ground ranged from 1.0 to 2.1 m/s and was limited by oscillation of the poles at higher speeds. Position information for the boat was collected with a GPS receiver (Model GPSMap-76CSX, Garmin, Olathe, Kan.).

Paired missions (i.e., tracking surveys with spatially and temporally similar routes for both the AUV and boat) were conducted in Stephens Passage near Portland Island and Lynn Canal near Point Retreat. Survey routes varied from zigzag to straight-line transects, with offsets (i.e., parallel distance) from the mooring grid ranging from 200 to 400 m. During several missions the AUV was programmed to loiter (i.e., circle) at locations along the transect to enhance transmitter detec-

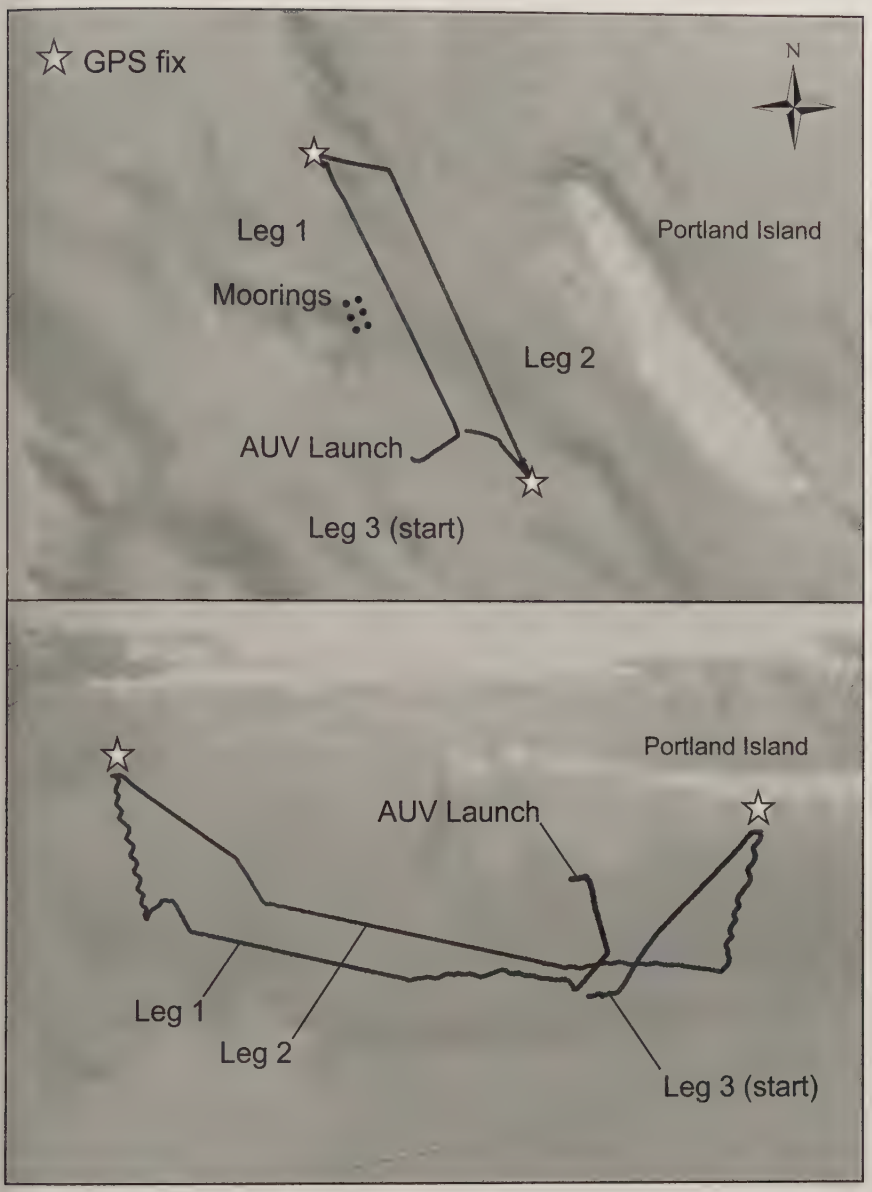

Figure 3.—AUV tracking mission conducted west of Portland Island near Juneau, Alaska (58.34° lat., -134.78° long.), during 2010 showing both the overhead (upper panel) and side (lower panel) view. The reference transmitter moorings, launch, recovery, and GPS fix locations are indicated. The AUV submerged to 80 m depth with programmed offset (parallel distance) from the mooring grid of 200 m (Leg 1) and 400 m (Leg 2), and surfaced at the end of each leg to obtain a GPS fix.

tions and position estimates. Transect length was approximately 2,700 m, and both single and multiple-leg (i.e., sequential transects differentiated by a 180° change in heading) missions were conducted (Fig. 3).

The AUV surveys were conducted between 30 and 80 m below the surface with a flat trajectory once the programmed cruising depth had been reached (Fig. 3). During missions with multiple legs, GPS fixes were obtained at the beginning and end of each transect. The boat followed behind the AUV using an acoustic ranger to communicate with the vehicle's acoustic modem and the acoustic telemetry gear (i.e., the boat's receiver and hydrophones, and the transmitter attached to the AUV) to actively monitor the position and depth of the submerged AUV. Telemetry data obtained during the AUV and boat surveys included time-stamped records identifying the reference transmitters and tagged animals detected, signal strength, environmental sensor data, and the corresponding position of the AUV and boat (latitude, longitude).

Both a fixed hydrophone (standard configuration used during the study with hydrophone at 1 m depth and oriented vertically) and towed hydrophone (50 m cable attached to a support tether with an 18 kg weight, and hydrophone oriented horizontally) were used during a separate boat survey at Point Retreat to increase hydrophone depth and compare performance of these two vessel-based tracking methods. The hydrophones were connected to separate receivers and used concurrently to record reference transmitters within the area.

Depth varied for the towed hydrophone depending on the ambient currents and vessel speed over ground. Based on the angle of the tether, estimated depth averaged 3 m when traveling at speeds between 1.6 and 2.0 m/s (3.2–4.0 kn) and 19 m for speeds between 1.0 and 1.3 m/s (2.0–2.5 kn), although fluctuations in depths were periodically observed due to interactions between vessel speed over ground, prevailing currents, and surface conditions. The orientation of the towed hydrophone, also indicated by the angle of the tether, ranged from nearly horizontal (3–8°) at faster speeds to a depressed angle of 25–30° at slower speeds. Ten consecutive, straight-line transects (five at the slower speed and five at the faster speed) were conducted, alternately running southeast and northwest with a 200 m offset from the transmitter moorings. Leg speed was randomly selected. Tracking success and the number of detections recorded were used to compare the two methods.

Data Analysis

Tracking results for the paired missions were analyzed by mission leg. Legs where the AUV and boat remained parallel to the mooring grid (i.e., consistent offset distance) and where both tracks were spatially and temporally equivalent provided comparable data. AUV and boat tracks were evaluated using data visualization software (Eonfusion, Myriax, Inc., Hobart, Tasmania, Australia) to determine if these criteria (i.e., consistent offset distances from mooring, and spatially and temporally similar survey routes) were met. GPS readings recorded every 1–2 s provided an accurate track of the boat route. Since the AUV did not record GPS fixes while submerged, its route was recorded in an analogous 2 s interval from the dead reckoning computations. Position estimates were rectified in post processing. The error between the most recent calculated position at depth and the new GPS position acquired at surfacing was smeared across the submerged point estimates of that leg using the AUV host software's "RENAV" feature. Boat tracking data from the transmitter placed on the AUV (previously described) and comparisons of the expected (i.e., programmed) and actual start/end locations of the AUV were used to evaluate the veracity of the estimated route.

The tracking performance analysis was based primarily on telemetry data from the reference transmitters, which provided acoustic targets at known locations and depths. Observations of the mobile targets (i.e., tagged Sablefish and king crab) were used to supplement the reference transmitter data, since it was not possible to verify their actual positions. Tracking results were categorized in four ways: tracking success, detection rate, reception range, and transmitter signal strength (also referred to as signal power).

Tracking Success

Tracking success was defined as the proportion of reference transmitters deployed at each depth and study site that were detected at least once per mission leg. AUV and boat survey results were tested for differences in tracking success for transmitters deployed at shallow (20 m) and mid-water (100 m) depths. Differences were apparent for transmitters at deeper depths (200 and 500 m), and were not analyzed formally. Tracking success was modeled with a mixed-effects model (Pinheiro and Bates, 2002). Tracking method (AUV or boat) was treated as a fixed effect in the model. Missions and mission legs were treated as random effects, allowing the experimental units to be considered as being sampled from a larger population of units and for missions from the two study sites to reasonably be combined. Treating mission leg as a random effect rather than a replicate was also more realistic because sampling conditions could not be reasonably repeated during subsequent legs due to changes in tide stage, weather conditions, and other factors.

Analyses were performed separately for shallow (20 m) and mid-water (100 m) depths. The sampling design was unbalanced as the numbers of legs were not equal among missions, and the tracking success proportions were arc-sine transformed prior to analysis to improve the homogeneity of variance (Neter and Wasserman, 1977). The models were fit using restricted maximum likelihood (REML) with the S-Plus statistical program (Version 7.0 for Windows TIBCO Spotfire Inc., Seattle, Wash.).

The normal mixed-effects model fit was defined as

$$y_{ijk} = \beta_0 + mission_i + leg_{j(i)} + tracking_k + \varepsilon_{ijk}, \quad (1)$$

where

y_{ijk} = arc-sine transformed tracking success for the j-th leg of mission i using the k-th tracking method;

β_0 = intercept;

$mission_i$ = i-th mission effect;

$leg_{j(i)}$ = j-th leg effect of mission i;

$\overline{tracking}_k$ = mean for the k-th tracking method for the AUV or boat;

$mission_i \sim N\left(0, \sigma_a^2\right)$;

$leg_{j(i)} \sim N\left(0, \sigma_b^2\right)$;

$\varepsilon_{ijk} \sim N\left(0, \sigma_e^2\right)$; and

$i = 1, 2, 3, 4$; $j = 1, 2, \ldots, 7$; 1, 2, ..., 5; or 1, 2, ..., 8; and $k = 1, 2$.

Errors were assumed mutually independent. The hypothesis test for the main fixed effect (tracking method) was H_0: $tracking_1 = tracking_2$. Diagnostic plots of standardized residuals (Pinheiro and Bates, 2002) from the fitted models were examined to assess the assumptions of constant variance and normality.

Detection Rate

Detection rate was defined as the number of reference transmitter detections recorded per minute during the mission leg. However, the time needed to complete a mission leg was not always the same for the AUV and boat due to differences in cruising speed over ground and ocean conditions. To make the tracking results comparable, the number of transmitter detections was standardized by the time the AUV and boat spent within reception range. Since the legs started before the transmitters were detected and ended as detections lessened, the time between the first and last record was used as a proxy for the time the AUV and boat spent within reception range.

Occasionally, sporadic detections occurred at extreme ends of a leg, which distorted the time estimates used in the analysis; therefore the first 2.5% and last 2.5% of the records were discarded for each leg and tracking method before calculating the time within reception range. No records were discarded if a tracking method at a particular depth recorded less than four detections. Only one case had less than four detections, and these were not at extreme ends of the track when compared with the other records. This procedure for standardizing the data was also used to compare reception range and power.

The numbers of detections per minute were modeled the same as tracking success with a mixed-effects model (Equation 1). Specifically, y_{ijk} was defined as the number of detections per minute for the j-th leg of mission i using the k-th tracking method. The model was fit as described previously for tracking success.

Reception Range

Maximum range was defined as the greatest distance recorded from the transmitter to the vessel (AUV or boat), and was calculated as the hypotenuse of the horizontal distance from the vessel and the difference between the transmitter depth and vessel depth. Average maximum range was computed for each mission leg at each depth and study site. Maximum range for each leg was computed as the maximum ranges averaged over the detected transmitters. The three legs of Mission P8, which had no transmitters detected by the boat, were removed from the shallow-tag analysis since we were interested in the maximum range for detected transmitters.

Average maximum range was modeled the same as tracking success with a mixed-effects model (Equation 1). Specifically, y_{ijk} was defined as the maximum range for the j-th leg of mission i using the k-th tracking method averaged over detected tags. Since the modeled response of range was an average, variance weights in the model were defined as the numbers of observations used in computing the averages (Weisberg, 1985). Specifically, we assumed for Equation 1

$$\varepsilon_{ijk} \sim N\left(0, \frac{\sigma_e^2}{n_{ijk}}\right), \qquad (2)$$

where

n_{ijk} = number of tags detected for the j-th leg of mission i using the k-th tracking method.

Signal Strength (power)

Average maximum power was computed for each mission leg at each depth and study site. Maximum power for each leg was computed the same as maximum range (i.e., the maximum power for detected transmitters was averaged over detected tags). Similar to range reception, the three legs of Mission P8 that had no transmitters detected by the boat were removed from the shallow-tag analysis since we were interested in the maximum power for detected transmitters. Average maximum power was modeled the same as tracking success with a mixed-effects model (Equation 1) and variance weights defined in Equation 2. Specifically, y_{ijk} was defined as the maximum power for the j-th leg of mission i using the k-th tracking method averaged over detected tags.

Fixed vs. Towed Boat Hydrophones

A normal mixed-effects model similar to Equation 1 was used to determine if hydrophone configuration (fixed vs. towed) and vessel speed were related to tracking success based on the auxiliary boat survey conducted at Point Retreat. Two of the variables defined previously were examined in this comparison: tracking success and detection rate. The number of reference transmitters (6) deployed at four depths (20, 100, 200, and 500 m) was the same as in the AUV vs. boat surveys. However, since only one mission of this type was performed and only six transmitters were present at each depth, tracking success (proportion of reference transmitters detected at least once per leg) was computed by pooling over all depths.

The hydrophone configuration (fixed or towed) was treated in the model as a fixed effect and vessel speed as a continuous variable. As in Equation 1, the survey legs were treated as a random effect. The model fit to the tracking success data is as follows:

$$y_{ij} = \beta_0 + hydrophone_i + leg_j + \beta_1 speed_{ij} + \varepsilon_{ij}, \qquad (3)$$

where

y_{ij} = arc-sine transformed tracking success for the j-th leg using the i-th configuration of the hydrophone;

β_0 = intercept;

$hydrophone_i$ = i-th configuration of the hydrophone (fixed or towed);

leg_j = j-th leg effect;

β_1 = regression coefficient for average vessel speed;

$speed_{ij}$ = average vessel speed for the i-th configuration of the hydrophone and the j-th leg;

$leg_j \sim N\left(0, \sigma_b^2\right)$;

$\varepsilon_{ij} \sim N\left(0, \sigma_e^2\right)$; and

$i = 1, 2$ and $j = 1, 2, \ldots, 10$.

Errors were assumed mutually independent. The hypothesis test for the main fixed effect, the hydrophone configuration, was H_0: $hydrophone_1 = hydrophone_2$, and the hypohesis test for the effect of vessel speed was H_0: $\beta_1 = 0$. The model was fit and diagnostics performed as described previously.

The fixed and towed hydrophones were also tested for a difference in detection rate—the number of reference transmitter detections recorded per minute during the survey leg. The duration of the survey leg was computed as the difference in time between the first and last transmitter detections. The detection rate was modeled the same as tracking success with a normal mixed-effects model (Equation 3). Specifically, y_{ij} was defined as the number of detections per minute for the j-th leg using the i-th hydrophone configuration. Similar to the analysis of the AUV versus boat data, models were fit separately for shallow (20 m) and mid-water (100 m) depths. Very few transmitters were detected at 200 m and therefore the data were not analyzed formally, and no transmitters at 500 m were detected by either fixed or towed hydrophone.

Results

Seawater Properties

Water temperatures during the Portland Island missions averaged 7.1°C near the surface (0–20 m) and 5.3°C at deeper depths (> 40 m). Although surface waters were warmer during later surveys near Point Retreat (averaging 8.5°C), temperatures at deeper depths

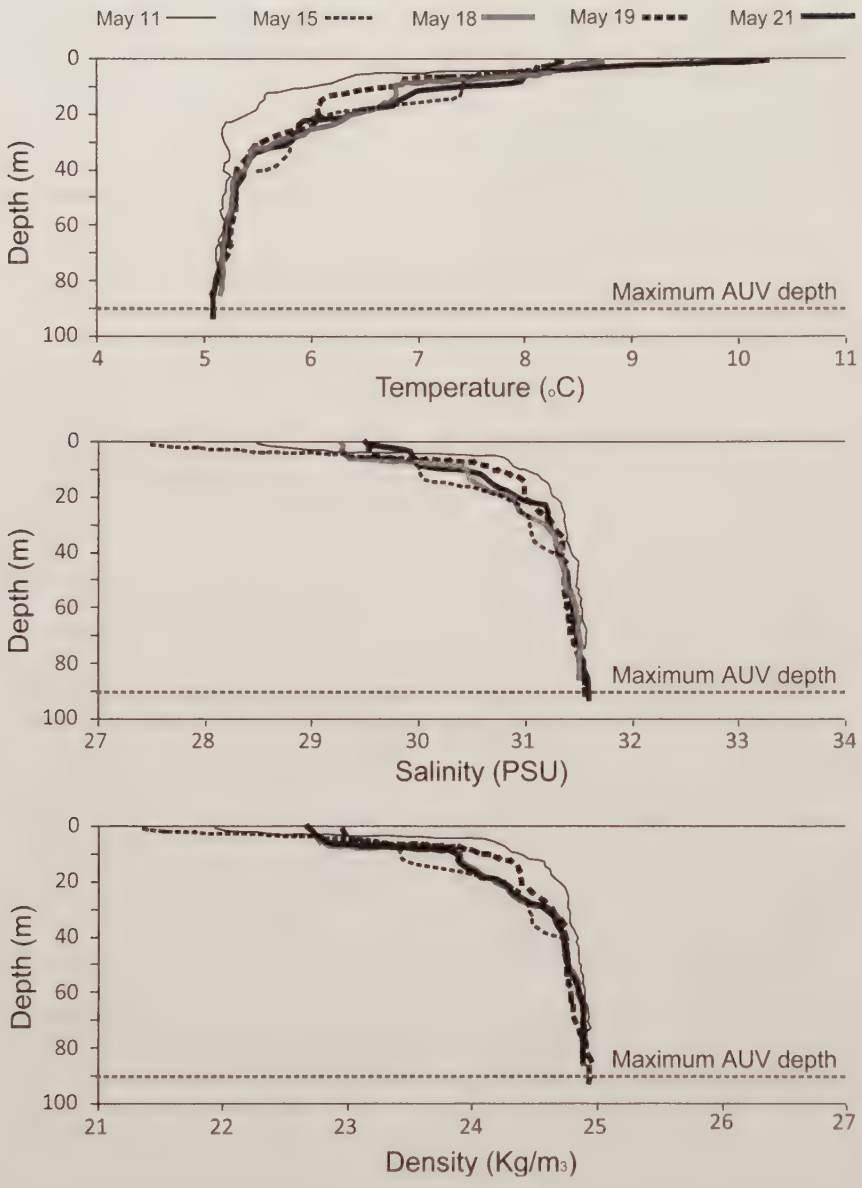

Figure 4.—Seawater properties determined from CTD (conductivity, temperature, and depth) data collected west of Portland Island near Juneau, Alaska, during May 2010. Water density is calculated using temperature and salinity data. Maximum operating depth for the AUV is indicated. Similar stratification patterns were observed at the Point Retreat site.

(average of 5.5°C) were comparable to those observed near Portland Island. Sea surface salinity averaged 30.3 near Portland Island and 29.4 near Point Retreat, with averages of 31.4 and 33.3 at deeper depths. Water density averaged 23.7 kg m^{-3} and 22.8 kg m^{-3} in surface waters, increasing to 24.8 kg m^{-3} and 26.2 kg m^{-3} at deeper depths. Surface waters were strongly stratified throughout the study, with a distinct thermocline, halocline, and pycnocline present in the upper 20 m (Fig. 4). The water column was more weakly stratified at deeper depths. For example, temperature differences near Portland Island and Point Retreat were greatest in the upper 20 m, (2.9°C and 3.6°C) compared to 20–40 m (0.7°C and 0.8°C), and greater than 40 m depths (0.2°C and 0.7°C). Similar trends were observed for salinity and density.

AUV vs. Vessel-based Tracking Performance

Four tracking missions, including two near Portland Island (P7 and P8) and two near Point Retreat (R2 and R3) were judged to have mission legs with comparable AUV and boat survey routes (spatially and temporally equivalent) that maintained a consistent offset from the transmitter moorings. The AUV submerged to a cruising depth of 80 m during missions P7, P8, and R3, and 50 m during Mission R2. Twenty-seven mission legs were used in the analysis, including 12 legs from Portland Island and 15 legs from Point Retreat.

Tracking Success

Tracking success (i.e., proportion of reference transmitters within the survey area detected during a leg) was significantly greater for the AUV than for the boat for transmitters deployed at both 20 m ($F = 105.8 \sim F_{1,26}$, $P < 0.0001$) and 100 m ($F = 10.5 \sim F_{1,26}$, $P = 0.003$). Diagnostic plots of standardized residuals from the model fits did not show strong evidence of non-constant variance or non-normality. The AUV was considerably more effective at detecting transmitters at deeper depth. Few transmitters were detected by the boat at 200 m depths, and only the AUV detected transmitters at 500 m depths (Fig. 5).

Confounding factors appeared to influence tracking success, especially during boat surveys. This was particularly evident during Mission P8 when no shallow (20 m) transmitters were detected by the boat during legs 2, 4, and 6. The heading during these legs (southeast) was with the current, which presumably would have minimized turbulence around the boat's hydrophone and improved signal reception. The southeast legs during this mission were offset 400 m from the transmitter moorings versus a 200 m offset during the northwest legs (Fig.

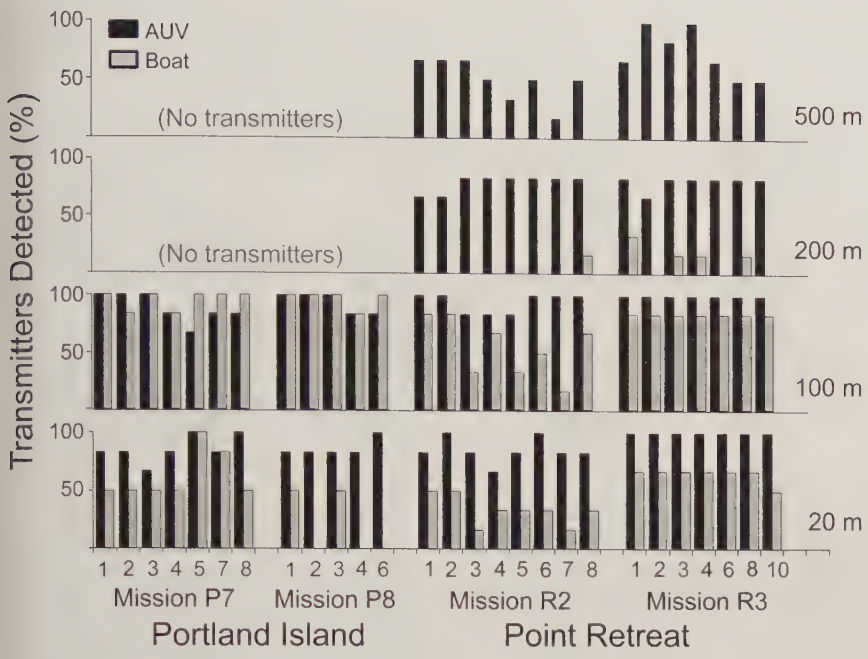

Figure 5.—Tracking success (percentage of the reference transmitters detected) by tracking method and mission leg for paired (AUV and boat) tracking missions in marine waters near Juneau, Alaska, during 2010. Transmitters were deployed at 20 and 100 m depths near Portland Island and from 20–500 m depths near Point Retreat. Transmitter depth is indicated in the right column legend. Mission legs excluded from the analysis are not shown.

3). However, transmitters at mid-water (100 m) depths were consistently recorded by the boat (Fig. 5) during both northwest and southeast legs, suggesting that other factors were involved.

Tracking success for the boat was consistently lower during Mission R2 than Mission R3. Similarly, the percentage of mid-water (100 m) transmitters recorded during southeast legs of Mission R2 was typically less than the northwest legs, again suggesting that local conditions influenced tracking results. Tracking success was remarkably similar for 20 and 100 m transmitters during Mission R3, particularly when compared with results from Mission R2. Differences in tracking success between and within AUV missions were minimal, especially for 20, 100, and 200 m transmitters (Fig. 5).

Detection Rate

The detection rate (i.e., the number of transmitter detections per minute during a leg) was significantly greater for the AUV at both 20 m ($F = 7.0 \sim F_{1,26}$, $P = 0.01$) and 100 m ($F = 58.5 \sim F_{1,26}$, $P < 0.0001$) depths, principally because no shallow-water (20 m) transmitters were detected by the boat during legs 2, 4, and 6 of Mission P8. When these legs were excluded from the analysis, the detection rates of the AUV and boat were not significantly different for transmitters in shallow water. Diagnostic plots of standardized residuals from the model fits did not show strong evidence of non-constant variance or non-normality.

The AUV was more effective detecting transmitters at deeper depths. Detection rates for transmitters at 200 m depths were exceptionally low during boat tracks, and only the AUV detected transmitters at 500 m depths (Fig. 6). Compared to tracking success, detection rates between and within the paired missions were more variable for both the AUV and boat, and this measure of tracking performance is likely to be more reflective of differences associated with other factors.

Reception Range

Reception range (i.e., the maximum distance that the reference transmitters were recorded) for the AUV increased from 423 to 599 m for transmitters at 20 and 500 m depths, respectively (Fig. 7). During boat surveys, reception range averaged from 399 m for transmitters at shallow depths (20 m) to 626 m for transmitters at mid-water depths (100 m). The average maximum range was not significantly different between the AUV and boat for transmitters deployed at 20 m depths ($F = 1.8 \sim F_{1,23}$, $P = 0.19$).

In contrast, average maximum range for transmitters at 100 m depths was significantly greater for the boat ($F = 87.7 \sim F_{1,26}$, $P < 0.0001$). Diagnostic plots of standardized residuals from the model fits did not show strong evidence of non-constant variance or non-normality. The AUV and boat exhibited comparable reception range for transmitters deployed at 200 m depth, although this comparison should be viewed with caution since the boat estimate was based on only a small number of records. Only the AUV recorded transmitters at 500 m depth with an average reception range of 599 m.

Transmitter Signal Strength

Maximum signal strength (power) showed a substantial decline with depth for transmitters recorded during the boat surveys. In contrast, power was relatively constant for transmitters recorded by the AUV at depths of 20, 100, and 200 m, and declined substantially for transmitters at 500 m depths (Fig. 7). Average maximum power was significantly greater for the AUV than for the boat for transmitters at 20 m ($F = 12.2 \sim F_{1,23}$, $P = 0.002$) and 100 m ($F = 213.7 \sim F_{1,26}$, $P < 0.0001$). Diagnostic plots of standardized residuals from the model did not show strong evidence of non-constant variance or non-normality. Power was substantially less for transmitters detected by

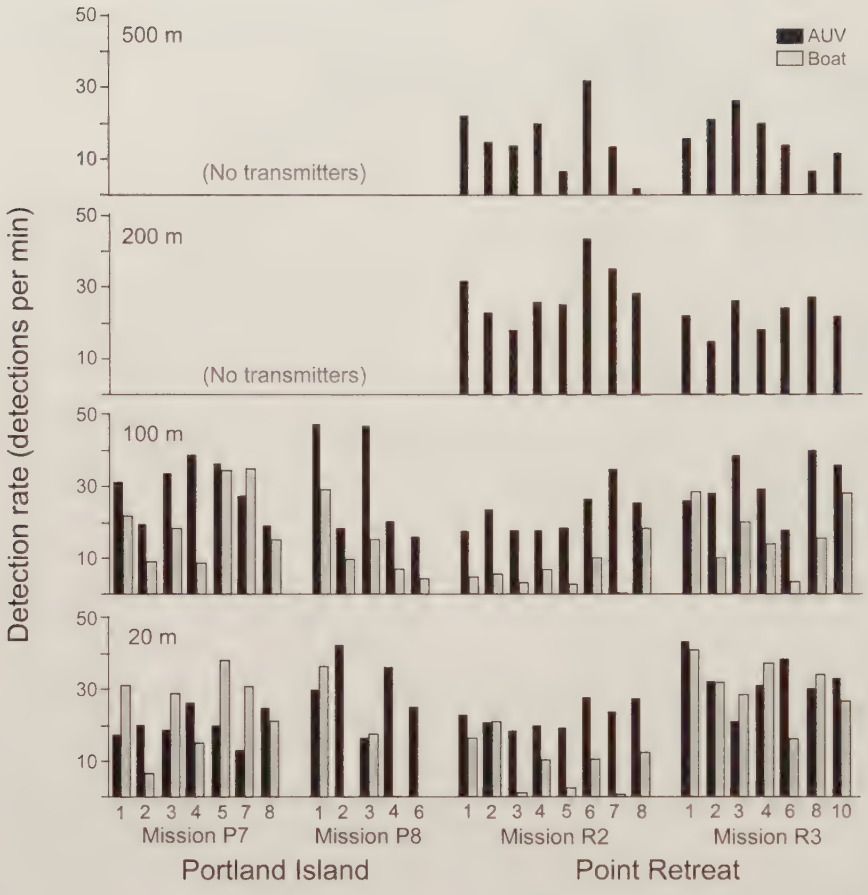

Figure 6.—Detection rate (number of reference transmitter detections recorded per min) by tracking method and mission leg for paired (AUV and boat) tracking missions in marine waters near Juneau, Alaska, during 2010. Transmitters were deployed at 20 and 100 m depths near Portland Island and from 20–500 m depths near Point Retreat. The boat detected too few transmitters at 200 m depths to be visible in this figure and no transmitters at 500 m depths. Mission legs excluded from the analysis are not shown.

the boat at 200 m depths, and only the AUV detected transmitters at 500 m depths.

Reception Patterns

Graphical displays of boat and AUV tracks showed different reception patterns. During boat surveys, transmitter detections were typically distributed widely along the transect route. In contrast, AUV detections were often truncated with relatively few transmitters detected on the periphery (Fig. 8). This pattern was not universal, suggesting that other factors were involved.

For example, AUV detections were more widely distributed during mission legs conducted during or near slack tide. The heading of the AUV, and therefore the orientation of the hydrophone, likely varied during the mission legs with strong current, which could also account for differences in reception pattern. It is possible that the straight-line transects used for the paired missions, although useful for minimizing adverse impacts from the prevailing currents and for standardizing AUV vs. boat comparisons, may also have biased the reception range estimates. Incidental detections, at greater distances than those recorded during the mission legs, were occasionally made at the end of the mission when the AUV had turned and was traveling to its recovery location.

Mobile Targets

Seven king crabs were tagged with acoustic transmitters and released in shallow water near Portland Island. The crabs, which had recently molted, averaged 197 mm in length, ranging from 185 to 210 mm. A variety of fish were caught with longline gear, including 34 Sablefish. Ten Sablefish were tagged and released in deep water near Point Retreat. The fish averaged 683 mm in length, ranging from 640 to 775 mm.

King crabs released near Portland Island were detected by both tracking methods. Three crabs were recorded during missions P7 and P8. One crab was recorded during every mission leg; the other two crabs were detected less frequently. The actual locations of the tagged individuals were not known, so the reception range was not determined. The AUV exhibited slightly better tracking success. Twenty-nine sightings (average = 2.1 crabs/leg) were recorded by the AUV compared to 23 sightings (average = 1.6 crabs/leg) for the boat. The number of detections recorded by the AUV during the paired missions was substantially greater, ranging from 4.3 to 5.8 times the number of detections observed during the boat surveys.

Tagged Sablefish released in deep water near Point Retreat were only detected by the AUV. Two tagged individuals were consistently recorded during the survey legs of Mission R2. A similar pattern was observed for legs 1–6 of Mission R3. No fish were detected during the last four legs of this survey, but these transects were conducted farther from the mooring grid and the fish may have been out of reception range.

Tracking Performance using Fixed and Towed Boat Hydrophones

Differences in vessel-based tracking performance were observed during the fixed and towed hydrophone comparison test conducted near Point Re-

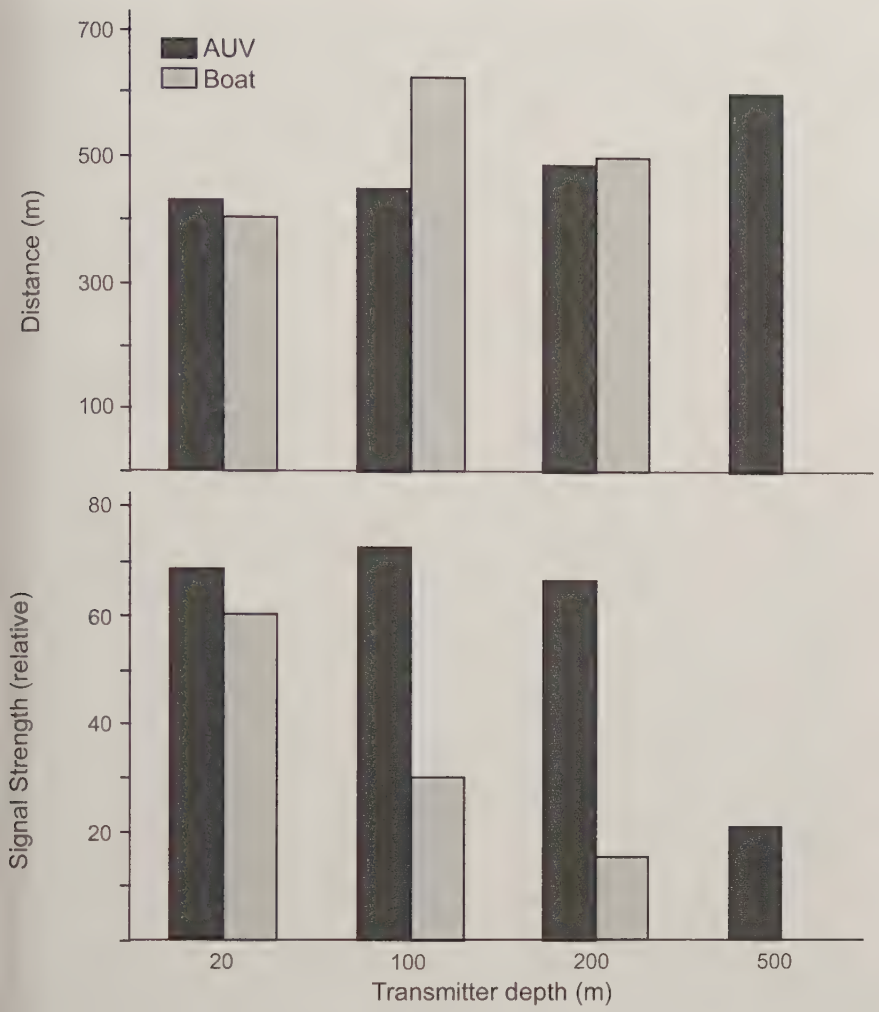

Figure 7.—Average maximum reception range (upper panel) and signal strength (lower panel) by tracking method and transmitter depth for reference transmitters detected during paired (AUV and boat) tracking missions in marine waters near Juneau, Alaska, during 2010.

treat. The fixed hydrophone exhibited significantly better tracking success ($F = 13.4 \sim F_{1,9}$, $P = 0.005$), detecting an average of 45.1% of the reference transmitters present compared to 33.3% for the towed hydrophone (Table 1). Tracking success was not significantly related to vessel speed ($F = 0.2 \sim F_{1,8}$, $P = 0.66$). Diagnostic plots of standardized residuals from the model fits did not show strong evidence of non-constant variance or non-normality.

With respect to detection rate, most (85.6%) of the transmitters recorded during the survey were detected by the fixed hydrophone. When accounting for depth, similar detection rates were exhibited by both the fixed (86.4% and 85.7%) and towed (15.1% and 14.9%) hydrophones for transmitters at 20 m and 100 m, respectively (Table 2). Although relatively few transmitters were detected at 200 m depths, the towed hydrophone recorded a greater percentage at the slower speeds (65.7%) compared to the fixed hydrophone (34.3%). Negligible detections were made by either tracking method at faster speeds (Table 2). Transmitters deployed at 500 m depths were not detected during the survey.

Based on the normal mixed-effects model, the fixed hydrophone had significantly greater numbers of detections than the towed hydrophone at 20 m depth ($F = 90.9 \sim F_{1,9}$, $P < 0.001$) and at 100 m depth ($F = 68.3 \sim F_{1,9}$, $P < 0.001$). Vessel speed was not a significant factor for both the 20 m transmitters ($F = 1.2 \sim F_{1,8}$, $P = 0.31$) and 100 m transmitters ($F = 3.6 \sim F_{1,8}$, $P = 0.09$). Diagnostic plots of standardized residuals from the model fits did not show strong evidence of non-constant variance or non-normality.

Discussion

Acoustic telemetry can provide detailed information on the distribution, movements, and habitat use of marine animals; however, tracking tagged individuals can be cumbersome and logistically challenging particularly in remote settings. The results of this study suggest that AUV's provide a viable alternative to conventional tracking methods. The four categories used to evaluate tracking performance—tracking success, detection rate, reception range, and signal strength—provided different insights into the capabilities of both vessel-based and AUV tracking methods.

Performance Metrics

Tracking success provided a direct measure of how effectively transmitters within the area were detected. Similarly, reception range provided functional information with direct application to field operations. Tracking success and range estimates are essential for designing and implementing effective tracking surveys, particularly in relation to the scope of the study and the time available for field operations (Grothues et al., 2005; Heupel et al., 2006; Simpfendorfer et al., 2008). The implications associated with detection rate (i.e., frequency that transmitters were detected) are more indirect, and are applicable when choosing the interval rate of the transmitter signal relative to the projected vehicle speed over ground and residence time within the signal radius during ensuing searches.

More detections typically improve the accuracy of location estimates, assist in screening out erroneous data, and indicate potential tracking success under less favorable conditions (Hedger et al., 2008; Bergé et al., 2012; Nielsen et al., 2012). Signal strength, although limited in its application due to confounding factors (particularly environmental conditions), provides a relative measure of tracking success and reception range. Transmitters with greater signal strength are more likely to be detected and exhibit greater reception range under most conditions. Signal strength can also be used to judge relative proximity and thereby provide simple positioning solutions (Grothues et al., 2009), but the inherent limitations must be understood relative to other methods.

These metrics help shape the tactical design of mission features (speed over ground, depth, shape and radius of maneuvers for calculating position, and constrained optimization of path). They are also relevant to designing payload control algorithms, whereby an AUV executes maneuvers that interrupt the programmed mission based on the telemetry data collected.

Payload control stands to mitigate one of the major operational disadvantages of AUV's in comparison to vessel-based tracking: the inability to respond to the telemetry information collected in real time. This approach would be analogous to someone changing course after hearing a transmitter signal in order to obtain more detailed information, and has numerous applications. Payload control is capable of autonomously following a particular tagged animal in a simple estuarine system (Forney et al., 2012) and further algorithmic developments promise to yield additional improvement (Xydes et al., 2013).

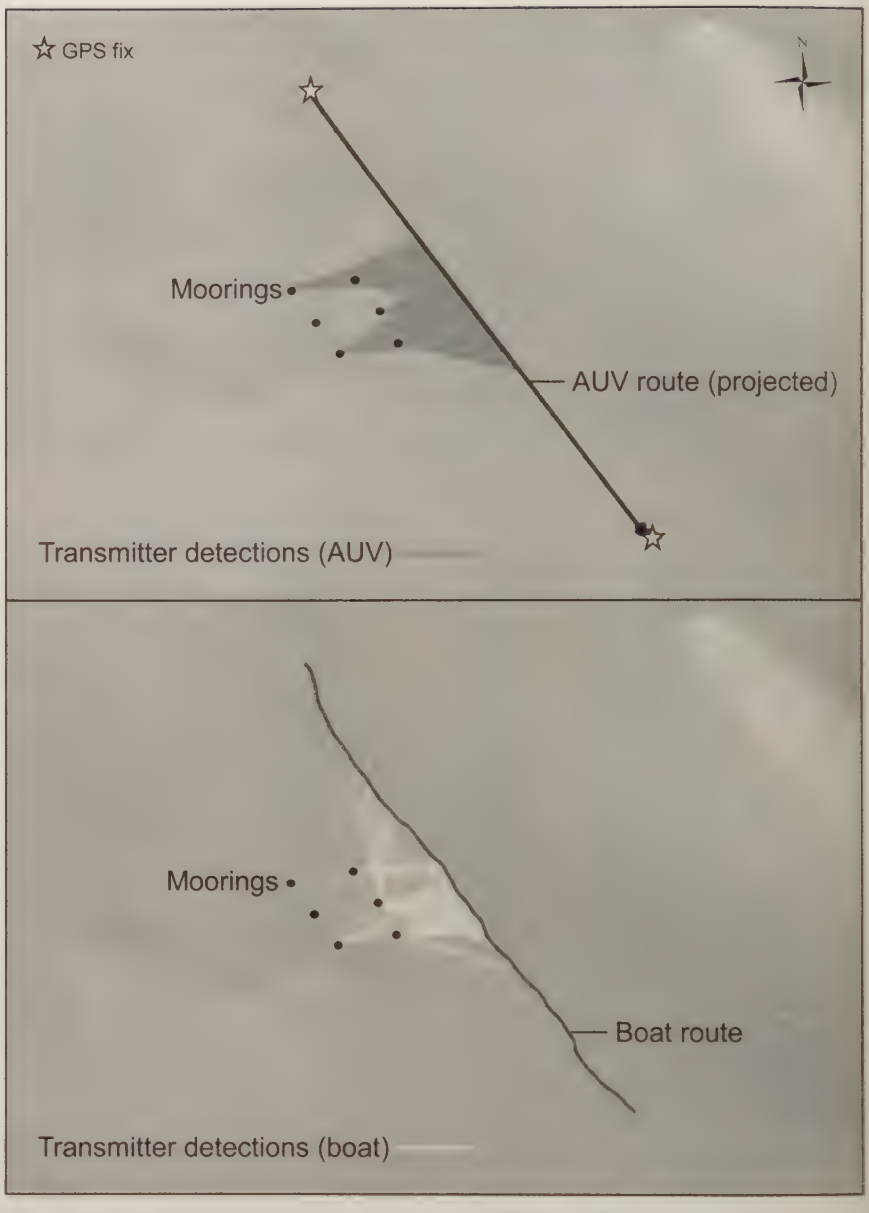

Figure 8.—Detection patterns (reference transmitters recorded along travel route) for the AUV (upper panel) and boat (lower panel) during a paired tracking mission conducted in marine waters west of Portland Island near Juneau, Alaska, during 2010. The reference transmitter moorings and GPS fixes for the AUV are indicated. The programmed offset (parallel distance) from the mooring grid for the AUV was 200 m. The AUV route was projected based on GPS fixes at the beginning and end of the mission leg.

AUV-boat Comparison

Overall tracking performance by the AUV was comparable or better than conventional vessel-based tracking. Tracking success and detection rate for the reference transmitters were significantly greater during the AUV surveys. Although less definitive in shallow waters (20 m), better detection rates by the AUV were particularly notable for transmitters at mid-water (100 m) and deeper depths. Signal strength exhibited a similar pattern, with the AUV exhibiting comparable power levels for transmitters in shallow water, and substantially greater power levels at deeper depth. Similar patterns were also observed for the mobile targets (i.e., tagged king crab and Sablefish), although the tracking data were auxiliary due to the limited scope of the

Table 1.—Tracking success (number and percentage of reference transmitters detected) for fixed and towed hydrophones during a vessel-based tracking survey in marine waters southwest of Point Retreat near Juneau, Alaska, during 2010. Twenty-four reference transmitters were present in the area. Mission leg and average vessel speed are indicated.

		Number of transmitters detected (%)	
Leg	Vessel speed (m/s)	Fixed hydrophone	Towed hydrophone
L1	1.9	11 (45.8)	9 (37.5)
L2	1.1	10 (41.7)	6 (25.0)
L3	1.1	12 (50.0)	13 (54.2)
L4	1.4	10 (41.7)	5 (20.8)
L5	1.8	10 (41.7)	9 (37.5)
L6	1.1	10 (41.7)	6 (25.0)
L7	1.1	13 (54.2)	10 (41.7)
L8	1.5	12 (50.0)	4 (16.7)
L9	1.9	10 (41.7)	9 (37.5)
L10	1.0	11 (45.8)	9 (37.5)
	All speeds	10.8 (45.1)	8.0 (33.3)

surveys and restricted transect patterns used during the study. Additional investigation is needed to better assess tracking performance for free-ranging individuals.

The relationship between tracking method and reception range was less apparent. Reception range was comparable for both methods at shallower depths. However, boat surveys exhibited greater range for transmitters at greater depths, particularly those at 100 m (Fig. 7), even though the fixed hydrophones were positioned near the surface and presumably would have been better able to detect shallow (20 m) tags.

Although less pronounced, AUV reception range increased steadily with increasing transmitter depth. Acoustic signals can be attenuated by sea surface noise and deflected by stratification associated with water temperature, salinity, and density (Jensen et al., 1994; Berger et al., 2008). Ocean stratification was observed throughout the study, particularly in the upper 20 m (Fig. 4), and may have impacted signal transmission in this layer. This condition may explain the reduced reception range at shallower depths.

The orientation of the hydrophone and straight-line survey pattern used during the study may also have been a factor. The boat hydrophones were mounted vertically on fixed struts, while the AUV hydrophone was oriented horizontally. The reception pattern of the hydrophone is essentially donut shaped, radiating out from the axis. When oriented horizontally, reception is greatest on the sides and substantially reduced in front or behind, creating a null when the AUV is traveling toward or away from the location. When free from other confounding factors, depth reception would likely be enhanced with this hydrophone orientation. Additional work is needed to compare tracking performance and reception patterns in relation to hydrophone orientation.

The most striking differences in tracking performance between the two methods were observed for transmitters at greater depths. Compared to the AUV, few transmitters were detected by the boat at 200 m depths and the signals received were relatively weak. Only the AUV recorded reference transmitters at 500 m depths. Although these signals were also relatively weak, average reception range was actually greater than observed for transmitters at shallower depths, suggesting that other factors were involved; most likely the vehicle's reception pattern and the restricted survey routes used during the missions.

A similar pattern was observed for mobile transmitters in deeper water. Tagged Sablefish at depths in excess of 500 m were detected exclusively by the AUV. The ability of the AUV to distance itself from the ocean surface (and associated sea surface noise) and descend below stratified marine layers appears to be a major advantage. Mobile surveys conducted at deeper depths also reduce the distance between the tracking vehicle and the tagged fish, which can substantially enhance tracking performance particularly when studying demersal or deepwater pelagic species.

Although tracking performance is a critical consideration, the overall effectiveness of collecting telemetry data

Table 2.—Number of reference transmitter detections recorded by fixed and towed hydrophones during a vessel-based tracking survey in marine waters southwest of Point Retreat near Juneau, Alaska, during 2010. Mission leg, hydrophone type, and transmitter depth are indicated. Percentage by vessel speed and transmitter depth is in parentheses.

	Transmitter depth (m)							
	20		100		200		500	
Leg	Fixed	Towed	Fixed	Towed	Fixed	Towed	Fixed	Towed
Slower vessel speeds[1]								
L2	462	25	495	41	1	2	0	0
L3	528	213	642	189	9	37	0	0
L6	395	15	331	34	0	1	0	0
L7	476	123	647	119	13	0	0	0
L10	862	107	625	96	0	4	0	0
All legs	2723	483	2740	479	23	44	0	0
	(84.9)	(15.1)	(85.1)	(14.9)	(34.3)	(65.7)		
Faster vessel speeds[2]								
L1	355	9	341	41	2	0	0	0
L4	198	0	152	31	0	1	0	0
L5	117	3	135	33	0	1	0	0
L8	493	70	226	11	1	0	0	0
L9	208	81	106	24	0	1	0	0
All legs	1371	163	960	140	3	3	0	0
	(89.4)	(10.6)	(87.3)	(12.7)	(50.0)	(50.0)		
All vessel speeds								
Total	4094	646	3700	619	26	47	0	0
	(86.4)	(13.6)	(85.7)	(14.3)	(35.6)	(64.4)		

[1]Ranging 1.0–1.3 m/s (2.0–2.5 kn).
[2]Ranging 1.6–2.0 m/s (3.2–4.0 kn).

with AUV's is inextricably linked to its operational performance. Several problems were encountered during the study, ranging from functional limitations of the vehicle to mechanical and electrical issues. AUV performance was regularly impacted by local conditions. Travel route integrity was routinely compromised when traveling against strong currents, although the impact varied with the survey pattern. Maneuvers designed to provide good geometry for determining transmitter position were severely affected by cross currents and loiter loops typically exhibited downstream elongation or incomplete, offset loops downstream from the current. Navigation was frequently hampered by the lack of ADCP bottom lock for missions in water much deeper than the AUV's operational depth limit. A number of hardware and software-related issues were also encountered.

Mechanical problems also occur with boats, and many of the other issues encountered will undoubtedly be addressed as AUV manufacturing, use, and servicing become more routine. Furthermore, some problems experienced during the study, such as operations in deeper-than-specified waters and areas with adverse environmental conditions (e.g., prevailing currents in excess of 1 kn, changes in tide stage exceeding 4 m), were knowingly self-imposed for the purpose of defining operational limits, and can be addressed by using AUV's with greater operating capabilities. Similar issues also apply to vessel-based operations in relation to vessel selection.

Improving Boat Tracking

Changes in equipment and tracking methods can circumvent some of the problems observed during this study with vessel-based tracking. Conventional boat tracking methods often utilize a move-stop-listen search pattern where the boat travels to a designated point and stops moving to reduce water turbulence around the hydrophone (to enhance signal reception) and collect telemetry data; the process is then repeated (e.g., Ng et al., 2007; Grothues et al., 2012).

While this approach can be effective, it is more time consuming compared to continuous surveys, particularly if the hydrophone is retracted from the water while in transit and must be redeployed. Tracking success is also dependent on the sampling interval and the reception range of the transmitters. Extended distances between sampling points can bias survey results, particularly when ambient conditions are less favorable and transmitter reception range is minimal or highly variable (Grothues et al., 2012).

However, sampling at shorter intervals is more time consuming, and can substantially reduce the area covered. Continuous but slower tracking speed would minimize this problem. However, unless tracking relatively sedentary species in localized areas, this approach has serious limitations; tracking mobile species over vast marine areas makes it necessary to cover extended distance in a reasonable period of time. Stronger structural supports to improve tracking speed when using fixed hydrophones and noise dampening techniques to lessen acoustic noise caused by water passing over the hydrophone (i.e., improving signal to noise ratio to increase transmitter reception) could substantially improve boat tracking success (Holland et al., 1985).

The comparison of vessel-based hydrophones (fixed vs. towed) during this study suggests that the fixed hydrophones provided better signal reception for transmitters at shallow and moderate depths (20 and 100 m). Both methods exhibited either marginal performance or were ineffective for detecting transmitters at deeper depths (200 and 500 m). Neither method was competitive with the AUV in terms of tracking success, overall reception range, signal strength, and tracking efficiency.

Fixed support structures provide precise information on the position, orientation, and depth of the hydrophone, substantially increasing the accuracy of the location estimates calculated for the transmitters. However, most fixed hydrophones are positioned at relatively shallow depths, and are therefore more susceptible to increased signal attenuation and deflection due to turbulence, sea surface noise, and ocean stratification. Towed sensors have been used extensively to obtain information on ocean conditions, and an improved system for towing acoustic hydrophones at deeper depths could substantially enhance the detection of deepwater transmitters by reducing reception problems associated with proximity to the surface and stratification within the ocean strata (Jensen et al., 1994; Berger et al., 2008). Disadvantages with towed hydrophones compared to fixed hydrophones include the risk of becoming entangled, difficulties inherent in standardizing the relative position, orientation, and depth of the hydrophone, and increased signal loss with increasing hydrophone cable length. These factors can adversely impact the quality and interpretation of the data, and are exacerbated at greater depths.

Future Research Needs

Based on this study, merging AUV technology and acoustic telemetry presents a tremendous opportunity to expand research capabilities for monitoring marine populations, and provides a powerful tool for integrating distribution and movement data with habitat and environmental information. These results suggest that AUV's have a distinct advantage for studying demersal and deepwater pelagic species. AUV sensors also provide proximal information on surrounding conditions, making it possible to integrate fish telemetry data with geomorphic and environmental information. Advances in data visualization software show promise for integrating and displaying these complex and often unwieldy data.

Tracking fish with AUV's does present significant challenges, including increased reliance on vehicle performance and navigation systems, pre-mission programming (e.g., accurately specifying survey routes and objectives), and knowledge of the survey area. Operational problems with

AUV's exist, but additional use, enhanced methods, and future advances will likely improve operational performance and assuage many of these limitations which are common to many AUV applications.

Additional work is also needed to further test the performance of telemetry systems for tracking fish. Specifically, more detailed information on system performance when the AUV is closer to the fish's depth and the ocean floor is needed, because there is potential for the change in angle between the tag's beam pattern (a directional sound pressure level bias: Grothues and Davis, 2013) to either increase or decrease positioning performance, or for bottom features to baffle transmission at the lower angle (Grothues et al., 2012).

Orientation of the hydrophone orthogonal to the AUV axis (presumably pointed at the seafloor) has never been compared and should be tested. This change could potentially resolve issues of baffling by the AUV's body and propeller, and also cause differences in the intercept geometries of the hydrophone's maximum sensitivity torus and the tag's beam pattern.

Payload control systems, by which data about ongoing tag detections is used to make navigation decisions, have been developed and tested for proof of concept (Forney et al., 2012), but only for following a single transmitter and never for the purpose of mapping multiple transmitters in a predefined search area. To the same end, search path geometries that maximize or find the best compromise between efficiency and the ability to accurately position a tag from synthetic aperture or sound pressure level methods (Nielsen et al., 2012; Grothues and Davis, 2013) should be modeled and then tested *in situ* on moving fish.

The use of a stereo hydrophone has likewise been tested for proof of concept on a small AUV, requiring an unwieldy boom system to separate the elements, but should be integrated in longer vehicles and tested against performance of single element systems in common environment trials to determine their value.

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Three Decades of U.S. Gulf of Mexico White Shrimp, *Litopenaeus setiferus*, Commercial Catch Statistics

RICK A. HART and JAMES M. NANCE

Introduction

The primary U.S. white shrimp, *Litopenaeus setiferus*, fishing grounds are located in the northern Gulf of Mexico (GOM), consisting of inshore and near-shore habitats favorable for *L. setiferus* survival and conducive to commercial fishing operations (Fig. 1) (Kutkuhn, 1962; Nance et al., 2010). This fishery has been studied extensively as early as the 1930's (Burkenroad, 1934, 1939) as it was the first fishery to fully exploit a Gulf of Mexico shrimp stock (Linder and Anderson, 1956).

The white shrimp fishery was primarily prosecuted in the shallower water of the bays and inshore estuaries using cast nets and haul seines (Klima et al., 1982). When the otter trawl was introduced to the Gulf shrimp fishery in 1915, it allowed fishermen to fish the deeper offshore habitats (Klima et al., 1982). Due in part to the widespread use of this gear by the 1930's (Klima et al., 1982), catches of white shrimp increased causing management to become concerned with the heavy levels of exploitation.

The fishery was already heavily capitalized beginning in the 1950's and, in their review, Condrey and Fuller (1992) noted that there was an early concern for the potential for both growth and recruitment overfishing. However, after WWII this concern abated as the discovery of the commercial brown shrimp, *Farfantepenaeus aztecus*, fishing grounds, and subsequent buildup of this more offshore fishery, relieved some of the fishing pressure exhibited on white shrimp stocks (Condrey and Fuller, 1992).

More recently, management concerns have become focused primarily on decreasing the potential for recruitment overfishing, while growth overfishing seems to be of little concern to managers (Nance et al., 2010, provided an overview of white shrimp management). Management attention has also been given to the identification and protection of essential fish habitat (EFH) for shrimp (Baker and Minello, 2010; Rozas and Minello, 2011).

Recent events affecting the white shrimp fishery, and nursery habitats in particular, have made it imperative that accurate documentation of catch histories for all of the GOM shrimp stocks be published (Hart et al., 2012). British Petroleum's Macondo exploration oil well catastrophe in 2010, Hurricanes Katrina and Rita (2005) and Ike (2008), sea level rise, and climate change all have the potential to impact essential white shrimp habitat and hence reduce shrimp production.

Here we have documented catch and effort statistics for the commercial *L. setiferus* fishery in the northern GOM. These catch statistics, in conjunction with state and Federal fishery independent surveys, are currently used as inputs in National Marine Fisheries Service (NMFS) stock assessment models estimating fishing mortality rates, spawning biomass, and annual recruitment numbers, with model outputs used as indices to gauge the status of the stock (Hart, 2012).

Methods

Records of the commercial harvest of *L. setiferus* have been collected for several decades, beginning in the 1950's (Kutkuhn, 1962). Commercial *L. setiferus* fishery statistics such as fishing effort, catch by size, and catch per unit effort (CPUE) are collected monthly throughout the GOM, using

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ABSTRACT—Gulf of Mexico, white shrimp, Litopenaeus setiferus, *catch statistics have been collected by NOAA's National Marine Fisheries Service for over 50 years. Recent occurrences such as natural and manmade disasters have raised awareness for the need to publish these types of data. Here we report shrimp data collected from 1984 to 2011. These 28 years of catch history are the time series used in the most recent Gulf of Mexico white shrimp stock assessment. Fishing effort for this stock has fluctuated over the period reported, ranging from 54,675 to 162,952 days fished. Catch averaged 55.7 million pounds per year, increasing significantly over the times series. In addition, catch rates have been increasing in recent years, with CPUE levels ranging from 315 lb/day fished in 2002, to 1,175 lb/day fished in 2008. The high CPUE's we have measured is one indication that the stock was not in decline during this time period. Consequently, we believe the decline in effort levels is due purely to economic factors. Current stock assessments are now using these baseline data to provide managers with further insights into the Gulf* L. setiferus *stocks.*

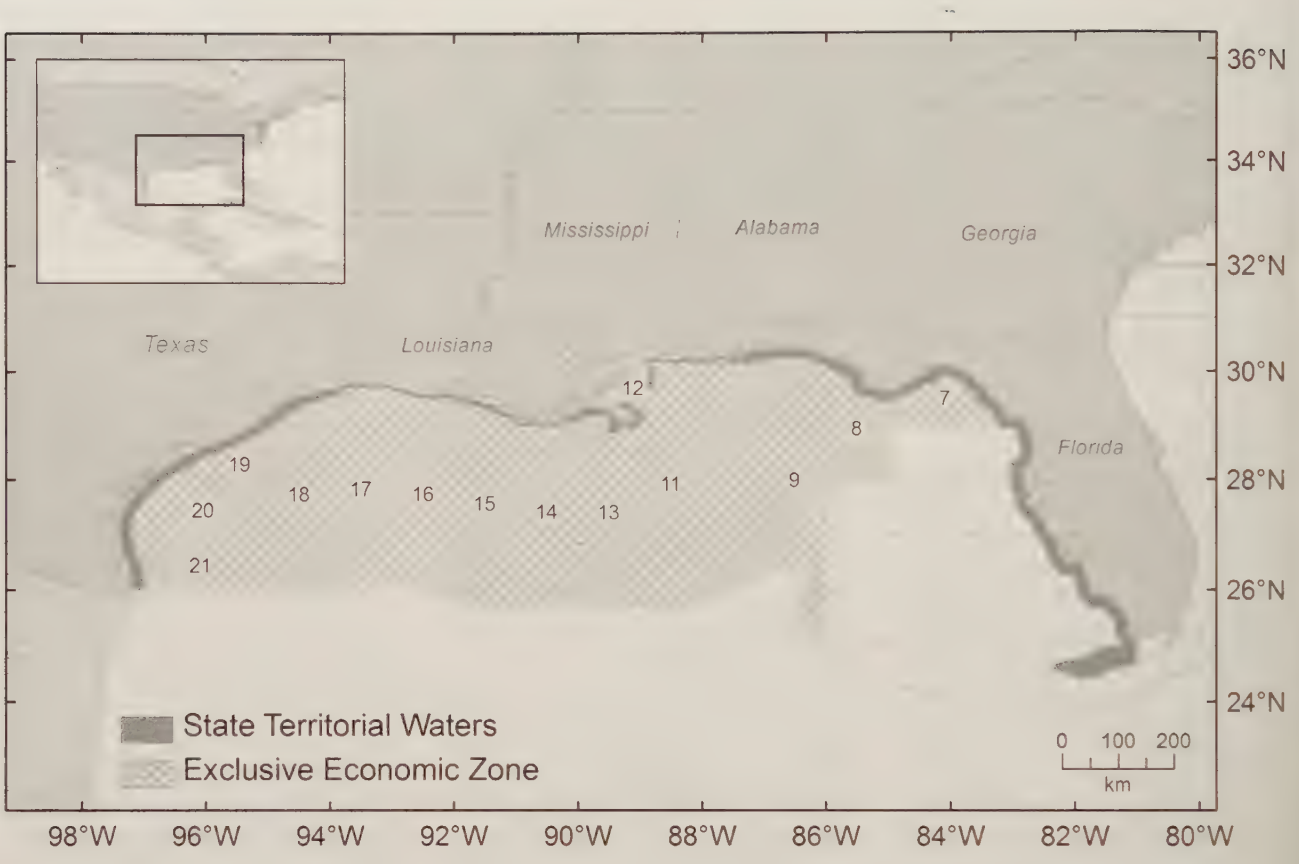

Figure 1.—U.S. Gulf of Mexico *Litopenaeus setiferus* fishing grounds, statistical zones 7–21.

standard collection methods (Nance et al., 2008).

NMFS port agents and state trip tickets record the daily operations and shrimp production of the commercial fisheries fleet operating within the boundaries of the U.S. GOM. To assist in the assignment of fishing locations, scientists have subdivided the U.S. Gulf of Mexico into 21 statistical subareas (Patella, 1975) (Fig. 1). These subdivisions are used by the port agents and state trip ticket system to assign the location of catches and fishing effort expended by the shrimp fleet on a trip by trip basis. The *L. setiferus* fishing grounds are located primarily within subareas 7–21 (Fig. 1).

Port agents randomly visit fishing ports throughout the Gulf of Mexico to interview fishing captains and/or crews and record data pertaining to trawling activity and the number of days fished (fishing effort). These data include the location, depth, and days fished, by statistical subarea; the species specific pounds and sizes of shrimp landed (heads off weight, i.e., tails); and the commercial value of the catch for each individual trip that a vessel has completed (Nance et al., 1989).

To calculate effort (i.e., the amount of time in hours the trawls are actually in the water fishing), catch, and CPUE statistics, we used the methods outlined in Nance et al. (2008). Beginning with pilot studies in 1999, an electronic logbook program (ELB) was initiated to augment shrimp fishing effort measurements. Gallaway et al., (2003a, b) provides an in-depth description of this ELB data collection program and data collection procedures. Beginning in 2006 these ELB data are used to supplement the effort and location data collected by NMFS port agents and state trip tickets (Nance et al., 2008).

The commercial shrimp statistics are entered into an Oracle[1] relational database maintained and managed by fisheries staff under the direction of the NMFS Southeast Fisheries Science Center, Miami, Fla. We have summarized those 1984–2011 catch statistics which are of primary importance for the establishment of baseline information that are incorporated in the NMFS *L. setiferus* stock assessments (Hart, 2012). We also examine temporal relationships among years for effort, catch, and catch rates using simple correlation and regression methodologies (Zar, 1984).

[1]Mention of trade names or commercial firms does not imply endorsement by the National Marine Fisheries Service, NOAA.

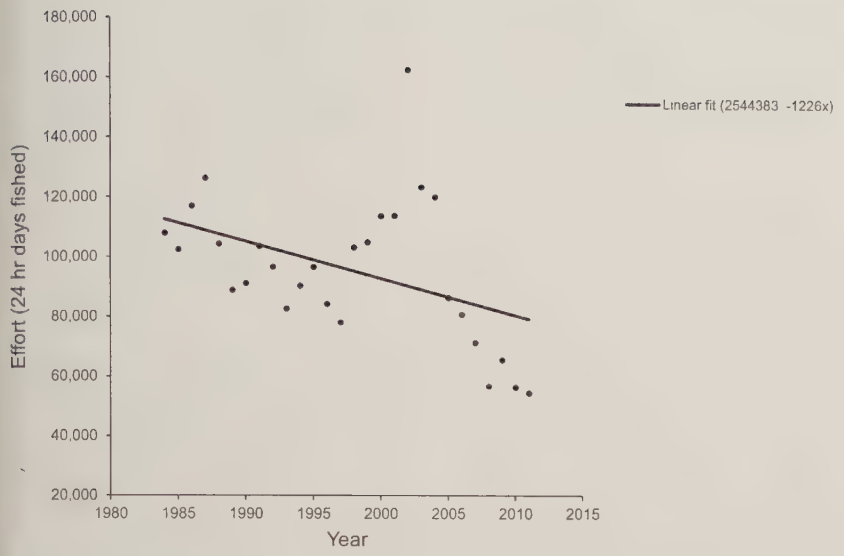

Figure 2.—*Litopenaeus setiferus* fishing effort vs. year, 1984–2011.

Table 1.—Gulf of Mexico, USA, *Litopenaeus setiferus* commercial catch statistics, 1984–2011.

Year	Catch (lb of tails)	CPUE (lb/day fished)	Effort (days fished)
1984	56,030,981	446	108,007
1985	58,912,565	523	102,532
1986	70,737,609	558	117,064
1987	53,443,843	417	126,427
1988	45,167,720	418	104,429
1989	36,573,614	397	88,939
1990	44,246,398	467	91,316
1991	45,796,242	549	103,642
1992	47,965,715	454	96,782
1993	39,061,982	458	82,746
1994	45,966,758	466	90,431
1995	49,262,652	503	96,801
1996	35,872,529	418	84,410
1997	39,114,562	491	78,261
1998	54,871,213	565	103,385
1999	54,956,418	490	105,200
2000	70,216,291	567	113,953
2001	53,391,418	421	114,103
2002	53,348,737	316	162,952
2003	60,996,687	524	123,715
2004	72,873,648	606	120,384
2005	65,314,218	772	86,662
2006	86,216,341	1,030	80,963
2007	64,305,379	873	71,612
2008	63,728,659	1,175	56,999
2009	74,966,922	1,130	65,787
2010	59,520,631	1,060	56,641
2011	57,782,441	1,115	54,675

Results

Fishing Effort

Fishing effort, as measured in 24 h days fished (i.e., trawls in water) has shown fluctuations over the 28-yr time period presented in this analysis, ranging from 54,675 to 162,952 days fished (Fig. 2, Table 1). Effort values averaged 96,029 days fished, declining over the 28-yr time period, ($F=5.53$, $_{df=1, 26}$, $P=0.03$, $R^2=0.18$) (Fig. 2). Effort during the period of 1998–2004 was at record high levels with a record 162,952 days fished recorded in 2002. Effort levels are currently at the lowest levels on record with only 54,675 days fished in 2011.

Annual Shrimp Catch

Catch, as measured in shrimp tails, has been steadily increasing over the time series ($F=8.56$, $_{df=1, 26}$, $P=0.007$, $R^2=0.25$) (Fig. 3). From 1984 through 2011, *L. setiferus* catch averaged 55.7 ±12.5 million lb (SD) (Table 1). Record numbers of *L. setiferus* were caught in 2006 (86.2 million lb). In contrast, the lowest catch on record for this time series occurred in 1996 with only 35.9 million lb of *L. setiferus* tails harvested from statistical zones 7–21 (Fig. 3).

Catch Per Unit of Effort (CPUE)

Catch per unit of effort is reported as pounds of shrimp caught during a 24 h fishing day (lb per nominal day fished). Catch per unit of effort averaged 614 lb/day fished in statistical areas 7–21 (Table 1) during 1984–2011. Harvest rates over this time series ranged from 316 lb/day fished during 2002 to 1,175 lb/day fished in 2008 (Fig. 4), with CPUE increasing over this time series despite a trend of decreasing fishing effort ($F=32.7$, $_{df=1, 26}$, $P<0.001$, $R^2=0.56$).

Discussion

The goal of this work was to describe the GOM commercial white shrimp catch statistics. The collection of these commercial fishing statistics was initiated in the mid 1950's, about the time period when brown and pink

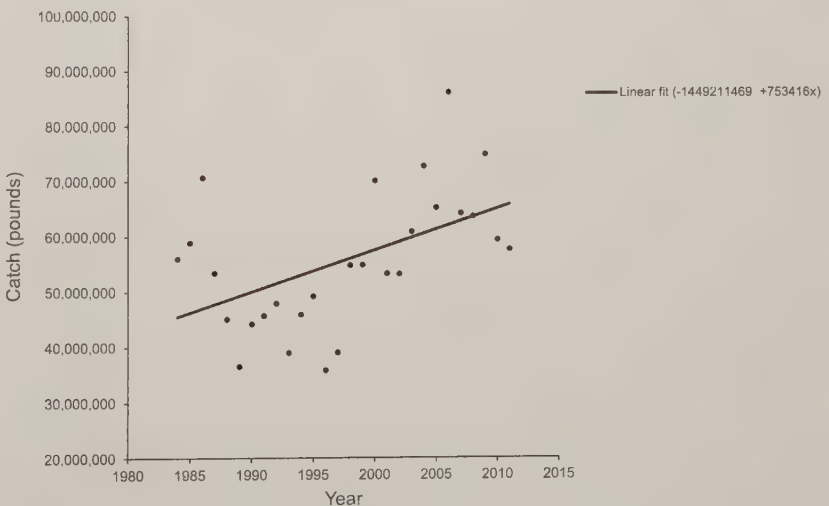

Figure 3.—*Litopenaeus setiferus* landings vs. year, 1984–2011.

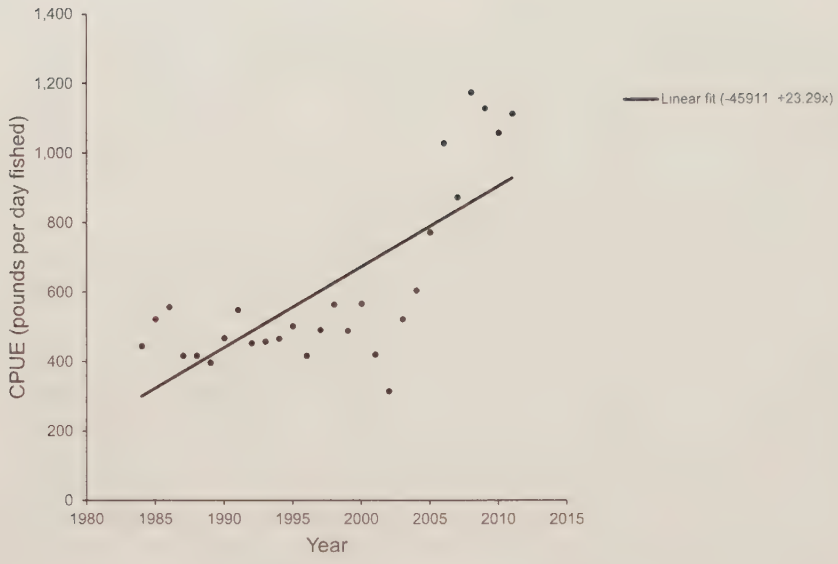

Figure 4.—*Litopenaeus setiferus* catch rate (CPUE) vs. year, 1984–2011.

shrimp overtook white shrimp in terms of total annual landings (Kutkuhn, 1962). These statistics have been used since that time to elucidate trends and changes in the fishery (Kutkuhn, 1962; Neal, 1975; Rothschild and Brunemeister, 1984; Neal and Maris, 1985; Nance et al., 2010; Hart, 2012). Catch and effort data are often used to develop CPUE trends which not only illustrate the fishing efficiency of the fleet, but also show the availability of the shrimp to harvest.

The CPUE of *L. setiferus* has long been used as an index of fishable biomass (Kutkuhn, 1962). While exploring the possible reasons for declines in white shrimp landings in 1957, Kutkuhn (1962) noted that, while landings declined abruptly in that year, the CPUE-based fishable biomass index did not parallel this drop in landings. In the time series we analyzed we are seeing an overall trend in declining effort and increases in catch and CPUE.

Effort is integral to CPUE, and the effort decrease we measured shows that effort in 2011 has been reduced by over 50% when compared to the highest levels recorded in the early years of the data set, e.g., 1998–2004. These declining effort levels are most likely due to adverse economic conditions that the fishing community has been experiencing during this time period (Travis and Griffin[2]).

While identifying and describing all of the factors contributing to the increase in effort from 1998–2004 and the dramatic decline in fishing effort after that time period is outside the scope of this paper, possible reasons for declining effort include: the devastation caused by hurricanes Katrina and Rita (2005) and Gustav and Ike (2008); an increase in competition with foreign shrimp products which has resulted in a decline in the price received by the fishermen (Keithly and Roberts, 2000; Haby et al., 2003); and an increase in marine fuel prices (Haby et al., 2003).

In the GOM white shrimp fishery, directed effort began to decline in earnest in 2005, interestingly coinciding with those major hurricanes which all made landfall on the Gulf Coast white shrimp fleet port areas. In addition, the recent Deep Water Horizon (DWH) oil spill in the Gulf of Mexico on 20 April 2010, resulted in approximately 40% of the U.S. Exclusive Economic Zone (EEZ) in the GOM having to be temporarily closed to commercial and recreational fishing (NOAA[3]). All of these factors have resulted in the number of federally permitted shrimp fishing vessels to steadily decline (NMFS unpublished data, personal observ.) since a fishing permit moratorium was put in place in 2006.

Concurrently with decreasing fishing effort, catch has increased significantly over the time series. Recently, catch is slightly greater than the long-term average. The disproportional changes in catch and effort have led to large increases in catch rates. The catch rate during the last year (2011) of our data set is about three times greater than the 1984 rate. Nance et al. (2010) found similar trends of increasing CPUE and declining effort in their analytical analysis of the white shrimp data set. Furthermore, our time series has five more recent years of data, revealing that the increasing CPUE and decreasing effort trends elucidated by Nance et al. (2010) have continued through 2011.

These record high catch rates we have recently measured are an indication that the *L. setiferus* population has remained large enough not to be negatively affected by current high levels of catch. This finding also is evident in the most recent GOM *L. setiferus* stock assessment modeling results (Hart, 2012) and is another indication that the fishery during this time period is not in a measurable decline.

The availability of decades of catch and effort data have led to the development of robust stock assessment models which have successfully measured the performance and "health" of the fishery in the past (Nance et al., 2008; Hart, 2012). The newest model has been successful in its ability to track these extreme changes in catch, effort, and catch rates (Hart, 2012). Therefore it is possible that long-term impacts

[2]Travis, M. D., and W. L. Griffin. 2004. Update on the economic status of the Gulf of Mexico commercial shrimp fishery. SERO-ECON-04-01 Rep., 10 p. Avail. online at http://sero.nmfs.noaa.gov/sf/socialsci/pdfs/EconUpdateGulfShr-Final.pdf.

[3]National Oceanic and Atmospheric Administration (NOAA). 2011. Deepwater Horizon/BP Oil Spill: 100 Days—a snapshot of NOAA's response. Avail. online at http://archive.orr.noaa.gov/dwh.php?entry_id=809. Accessed 4 April 2013.

of human-caused and natural disasters noted previously will be elucidated with the use of the new stock assessment model using the data presented herein. Having this long-term baseline data puts the NMFS in a unique position to better measure future biological and economic impacts on this fishery.

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Editorial Guidelines for the *Marine Fisheries Review*

The *Marine Fisheries Review* publishes review articles, original research reports, significant progress reports, technical notes, and news articles on fisheries science, engineering, and economics, commercial and recreational fisheries, marine mammal studies, aquaculture, and U.S. and foreign fisheries developments. Emphasis, however, is on in-depth review articles and practical or applied aspects of marine fisheries rather than pure research.

Preferred paper length ranges from 4 to 12 printed pages (about 10-40 manuscript pages), although shorter and longer papers are sometimes accepted. Papers are normally printed within 4-6 months of acceptance. Publication is hastened when manuscripts conform to the following recommended guidelines.

The Manuscript

Submission of a manuscript to the *Marine Fisheries Review* implies that the manuscript is the author's own work, has not been submitted for publication elsewhere, and is ready for publication as submitted. Commerce Department personnel should submit papers under a completed NOAA Form 25-700.

Manuscripts must be typed double-spaced throughout and submitted with two duplicate copies. The complete manuscript normally includes a title page, a short abstract, text, literature citations, tables, figure legends, footnotes, and the figures. The title page should carry the title and the name, department, institution or other affiliation, and complete address (plus current address if different) of the author(s). Manuscript pages should be numbered and have 1-inch margins on all sides. Running heads are not used. An "Acknowledgments" section, if needed, may be placed at the end of the text. Use of appendices is discouraged.

Abstract and Headings

Keep titles, headings, subheadings, and the abstract short and clear. Because abstracts are circulated by abstracting agencies, it is important that they represent the research clearly and concisely. Headings within each section must be short, reflect a logical sequence, and follow the rules of multiple subdivision (i.e. there can be no subdivision without at least two items).

Style

The entire text should be intelligible to interdisciplinary readers; therefore, all acronyms, abbreviations, and technical terms should be spelled out the first time they are mentioned. The scientific names of species must be written out the first time they are mentioned; subsequent mention of scientific names may be abbreviated. Follow the U.S. Government Printing Office Style Manual (1984 ed.) and the CBE Style Manual (5th ed.) for editorial style, and the most current issue of the American Fisheries Society's Common and Scientific Names of Fishes from the United States and Canada for fish nomenclature. Only journal titles, scientific names (genera and species), and vessel names should be italicized. Dates should be written as follows: 11 Nov. 1991. Measurements should be expressed in metric units, e.g. metric tons as t; other equivalent units may also be listed in parenthesis. Common abbreviations and symbols such as mm, m, g, ml, mg, and °C (without periods) may be used with numerals. The numeral one (1) should be typed as a one, not as a lowercase el (l). Write out the numbers zero through nine unless they form part of measurement units (e.g. nine fish but 9 mm).

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Figures include line illustrations and photographs (or slides) and must be cited in numerical order in the text. Figures are to be labeled with author's name and number of figure. Use Times Roman font (upper and lowercase letters) to label within figures. Avoid vertical lettering except for y-axis labels. Zeros should precede all decimal points for values less than one. Figures should be submitted as both laser-printed copies and computer software files. Figure legends should explain all symbols and abbreviations and should be double-spaced on a separate page at the end of the manuscript. Consider column and page sizes when designing figures. Please note that we do not print graphics in color.

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